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FIG. 1a

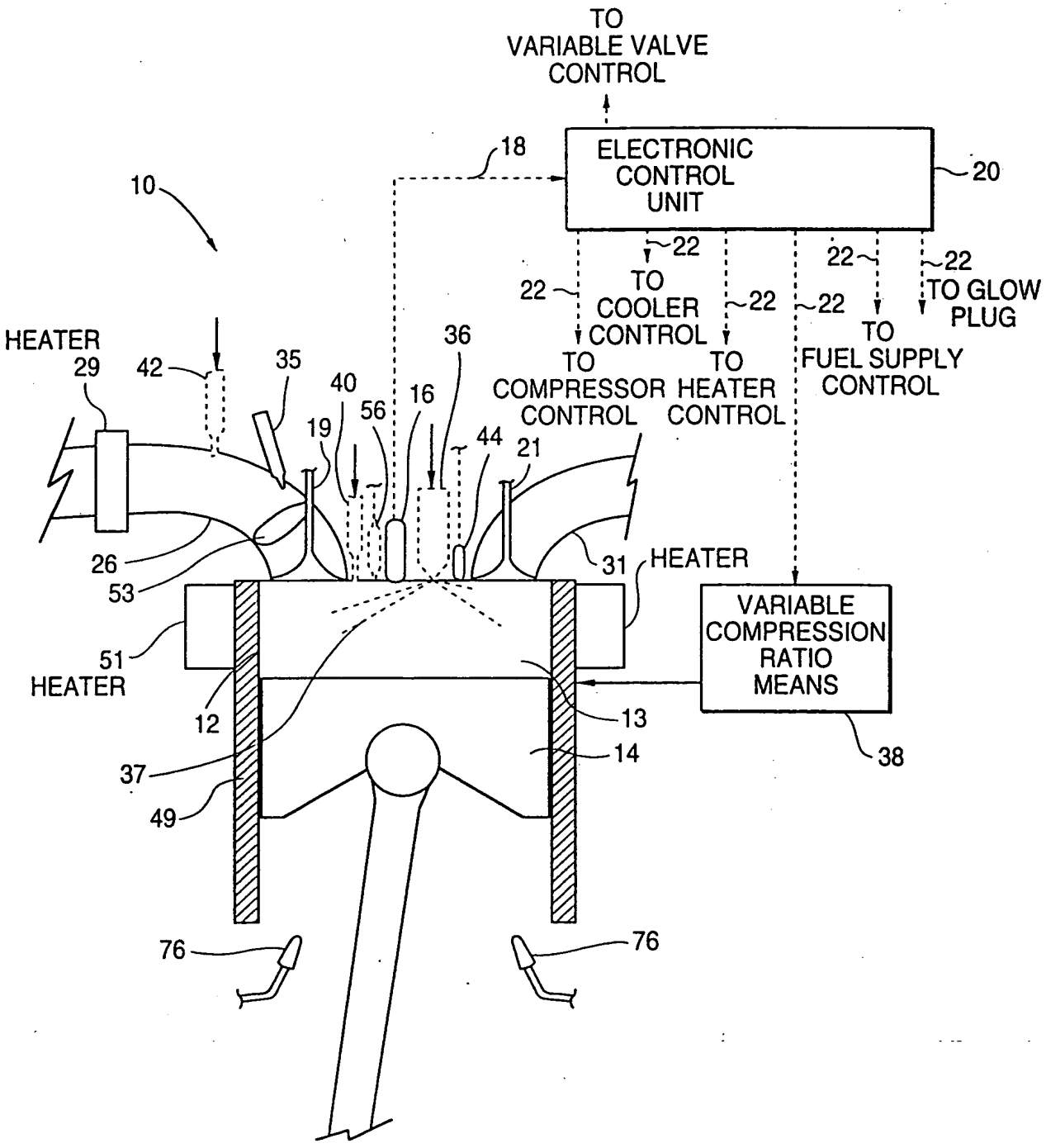

TO
VARIABLE VALVE
CONTROL
ELECTRONIC
CONTROL
UNIT
20
18
10
22
TO
COOLER
CONTROL
TO
COMPRESSOR
CONTROL
TO
HEATER
CONTROL
TO
FUEL SUPPLY
CONTROL
TO GLOW
PLUG
HEATER
29
42
35
40
56
16
36
19
44
21
26
53
31
HEATER
51
HEATER
12
37
49
13
14
VARIABLE
COMPRESSION
RATIO
MEANS
38
76
76

FIG. 1b

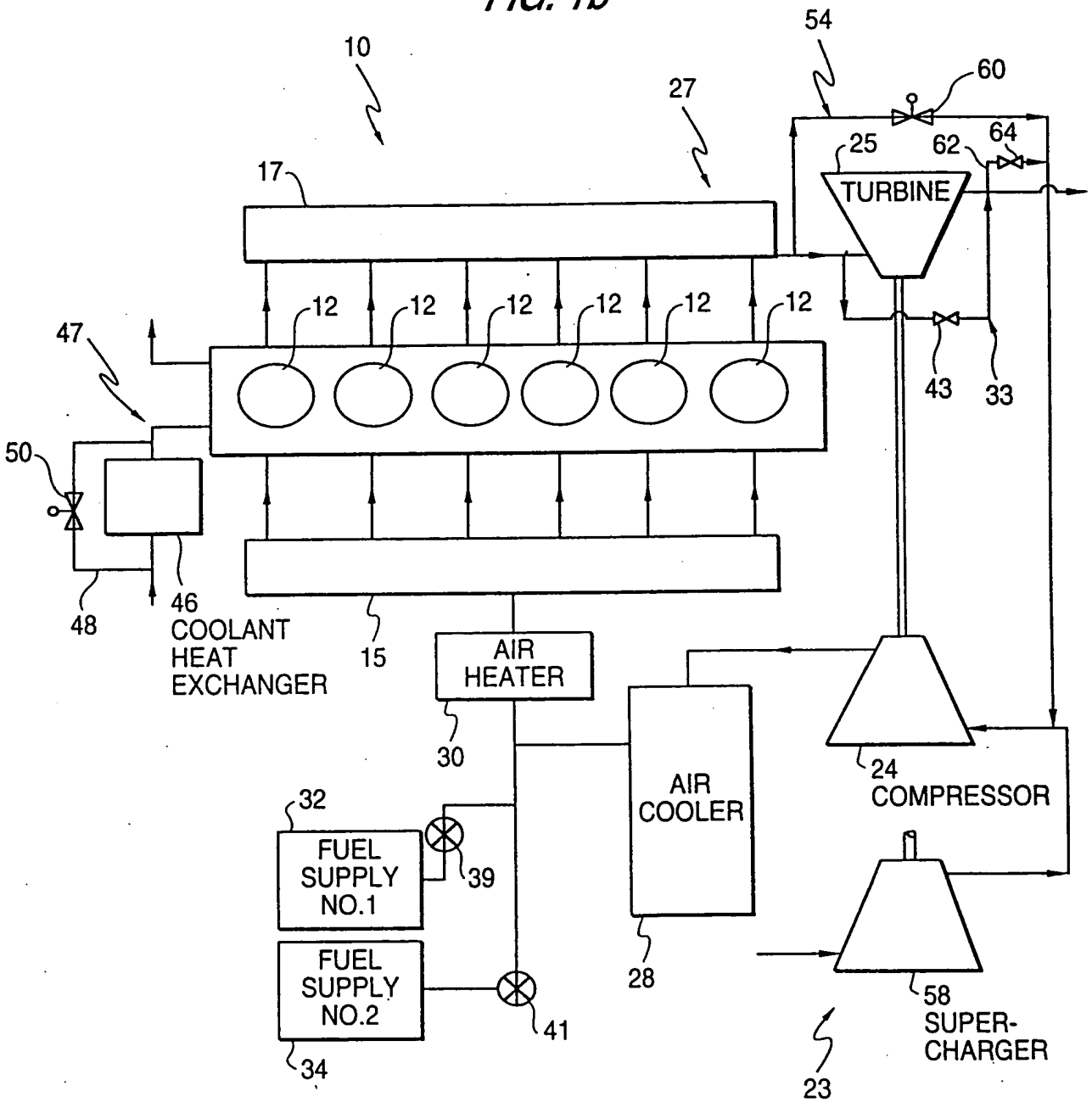

10
27
54
60
25
62
64
TURBINE
17
12
12
12
12
12
12
47
43
33
50
48
46
COOLANT
HEAT
EXCHANGER
15
AIR
HEATER
30
AIR
COOLER
24
COMPRESSOR
32
FUEL
SUPPLY
NO.1
39
FUEL
SUPPLY
NO.2
41
34
28
58
SUPER-
CHARGER
23

FIG. 2

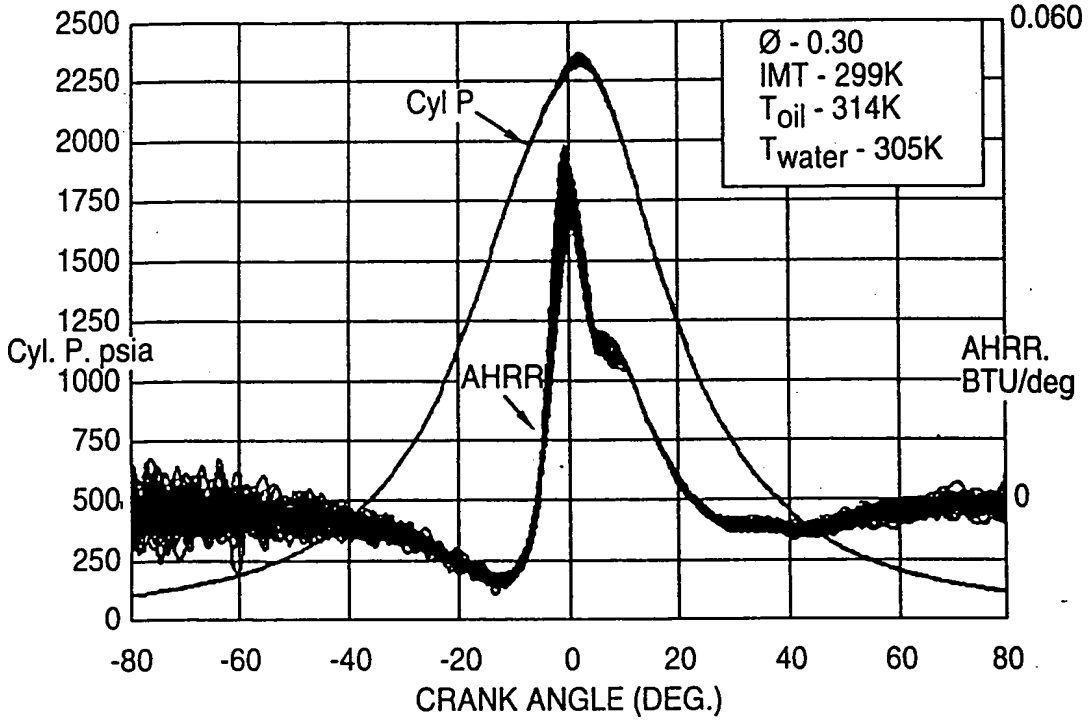

Ø - 0.30
IMT - 299K
T_{oil} - 314K
T_{water} - 305K
Cyl P
AHRR
Cyl. P. psia
AHRR. BTU/deg
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0.060
0
-80
-60
-40
-20
0
20
40
60
80
CRANK ANGLE (DEG.)

FIG. 3

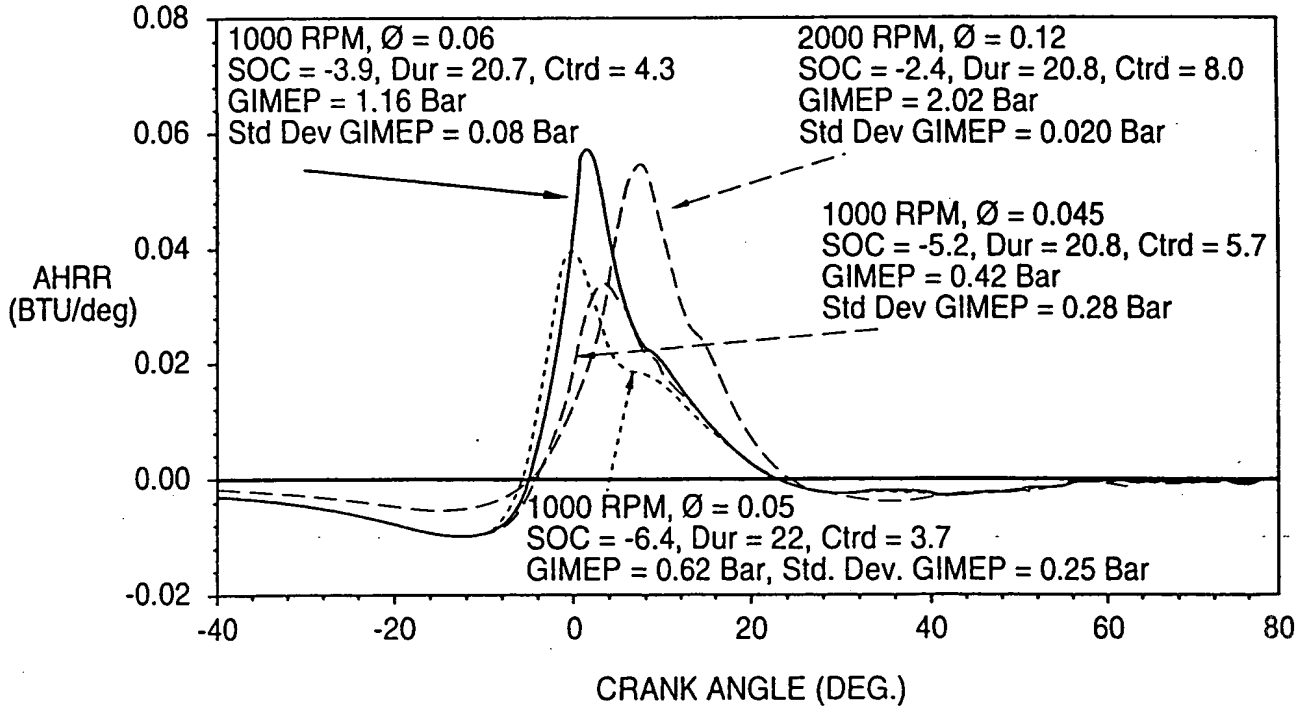

1000 RPM, Ø = 0.06
SOC = -3.9, Dur = 20.7, Ctrd = 4.3
GIMEP = 1.16 Bar
Std Dev GIMEP = 0.08 Bar
2000 RPM, Ø = 0.12
SOC = -2.4, Dur = 20.8, Ctrd = 8.0
GIMEP = 2.02 Bar
Std Dev GIMEP = 0.020 Bar
1000 RPM, Ø = 0.045
SOC = -5.2, Dur = 20.8, Ctrd = 5.7
GIMEP = 0.42 Bar
Std Dev GIMEP = 0.28 Bar
1000 RPM, Ø = 0.05
SOC = -6.4, Dur = 22, Ctrd = 3.7
GIMEP = 0.62 Bar, Std. Dev. GIMEP = 0.25 Bar
AHRR (BTU/deg)
0.08
0.06
0.04
0.02
0.00
-0.02
-40
-20
0
20
40
60
80
CRANK ANGLE (DEG.)

FIG. 4a

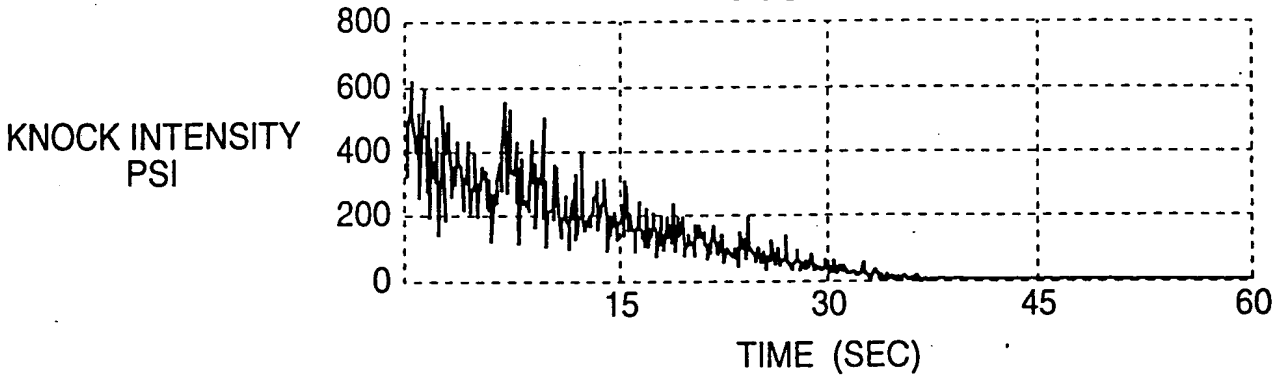


FIG. 4b

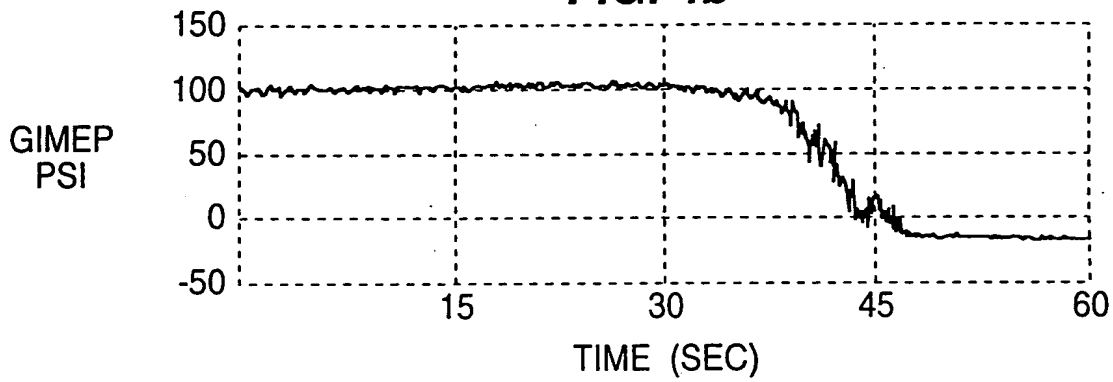


FIG. 4c

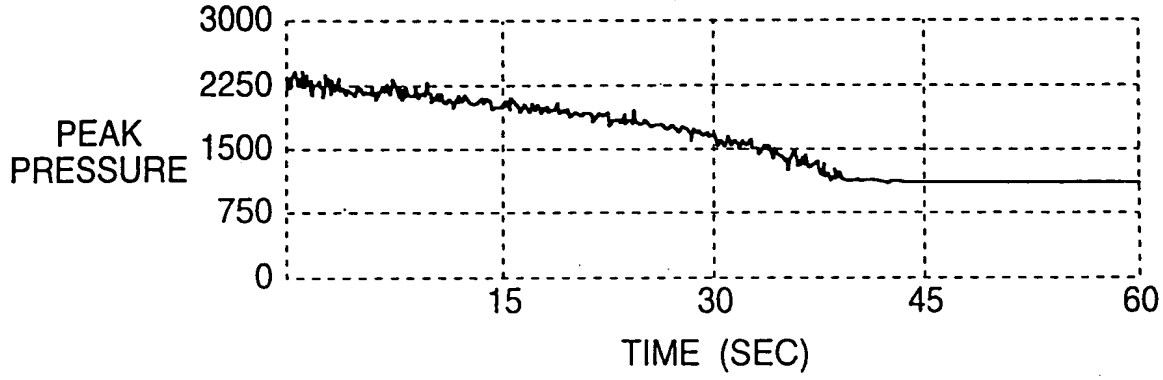


FIG. 5

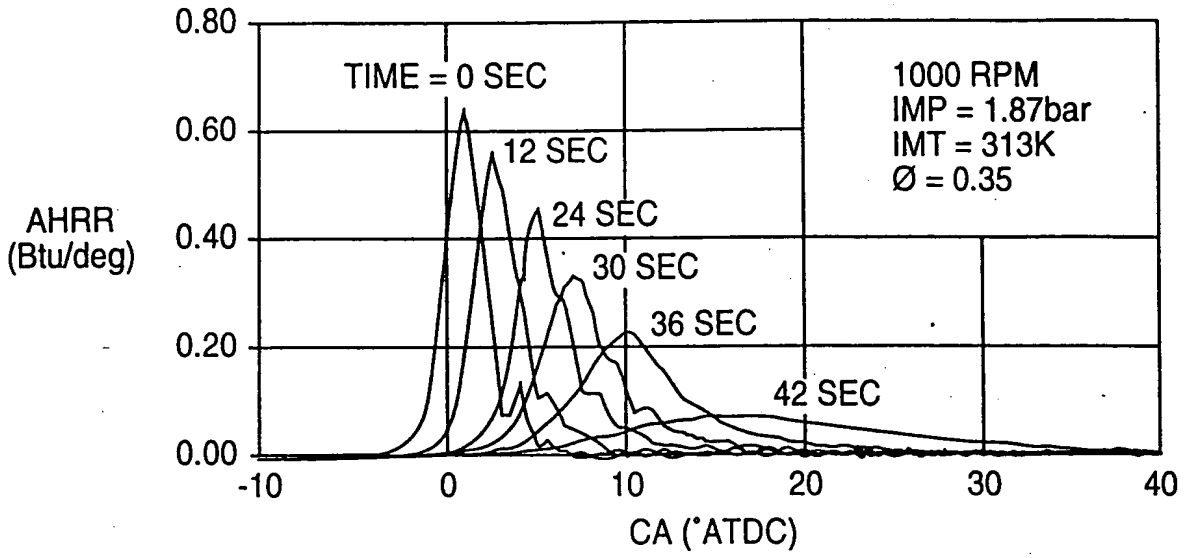

0.80
0.60
0.40
0.20
0.00
AHRR
(Btu/deg)
TIME = 0 SEC
12 SEC
24 SEC
30 SEC
36 SEC
42 SEC
1000 RPM
IMP = 1.87bar
IMT = 313K
Ø = 0.35
-10
0
10
20
30
40
CA (˚ATDC)

FIG. 6

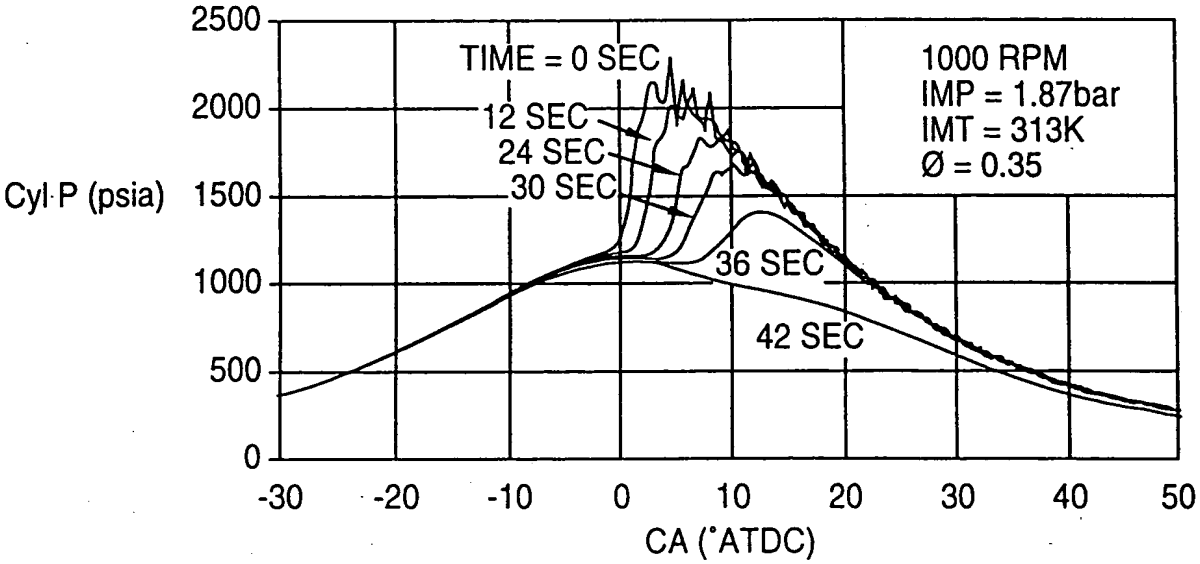

2500
2000
1500
1000
500
0
Cyl P (psia)
TIME = 0 SEC
12 SEC
24 SEC
30 SEC
36 SEC
42 SEC
1000 RPM
IMP = 1.87bar
IMT = 313K
Ø = 0.35
-30
-20
-10
0
10
20
30
40
50
CA (˚ATDC)

FIG. 7a

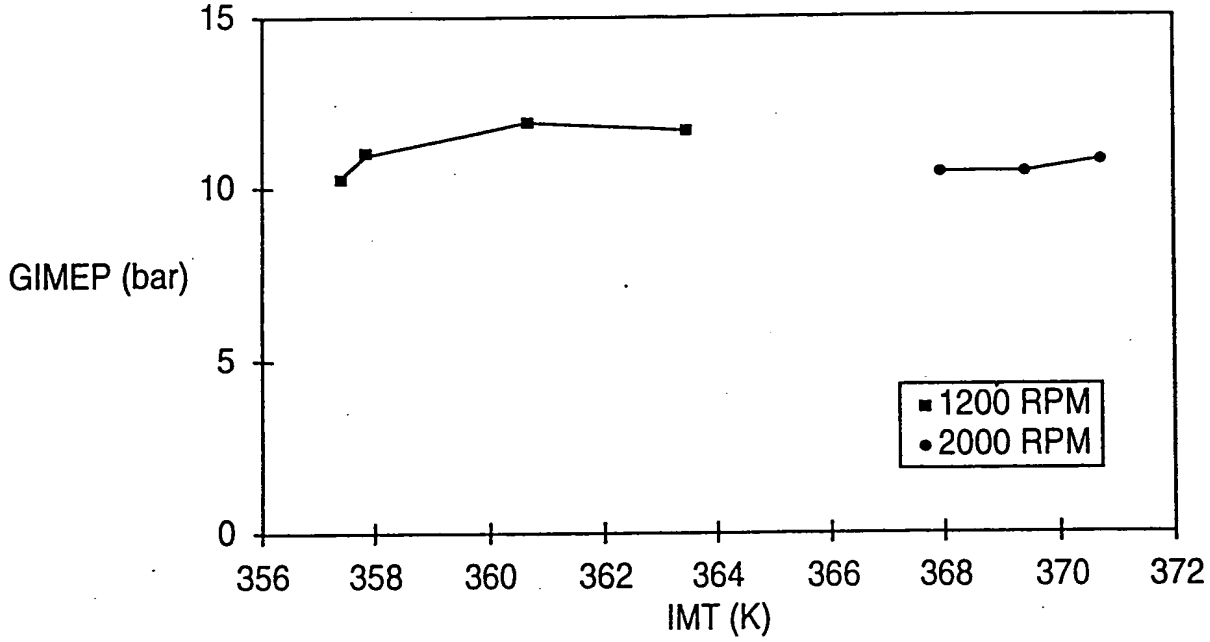

15
10
5
0
GIMEP (bar)
1200 RPM
2000 RPM
356
358
360
362
364
366
368
370
372
IMT (K)

FIG. 7b

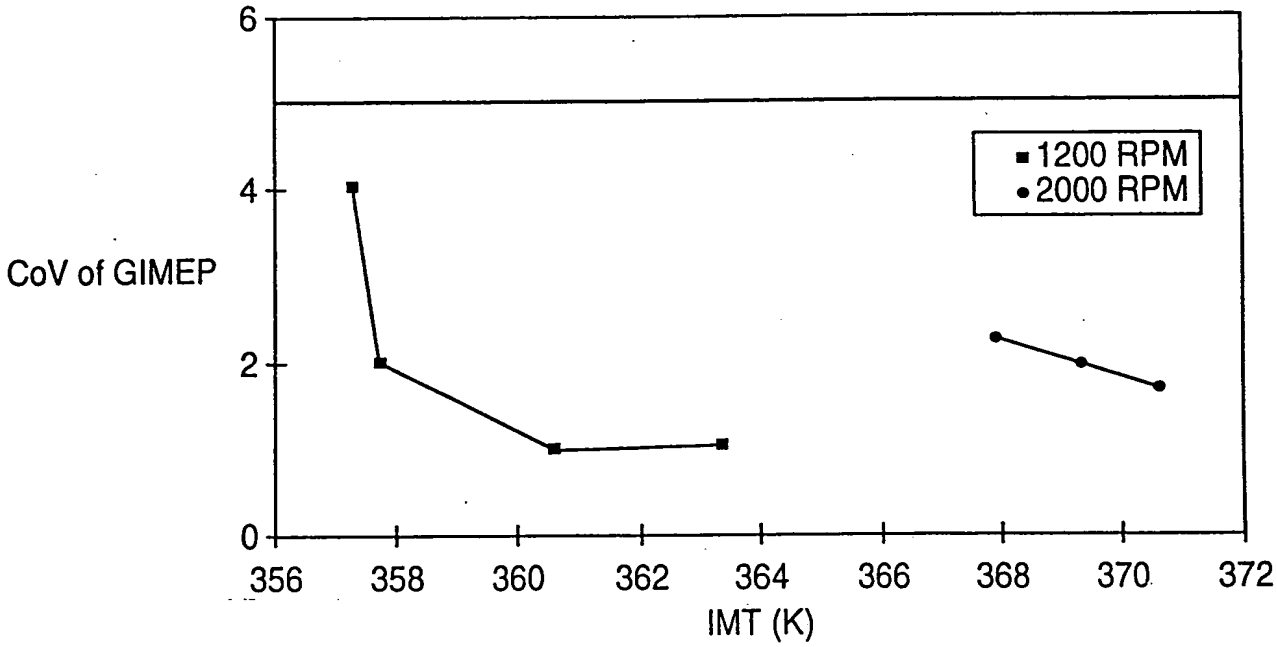

6
4
2
0
CoV of GIMEP
1200 RPM
2000 RPM
356
358
360
362
364
366
368
370
372
IMT (K)

FIG. 7c

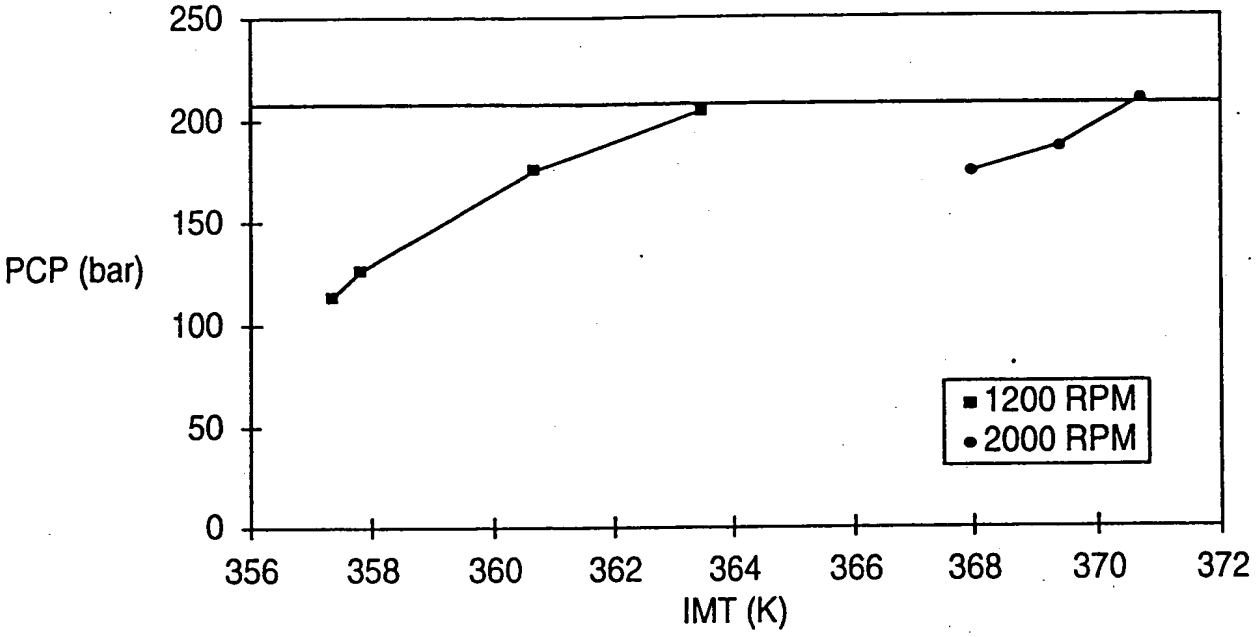

250
200
150
100
50
0
PCP (bar)
356
358
360
362
364
366
368
370
372
IMT (K)
1200 RPM
2000 RPM

FIG. 7d

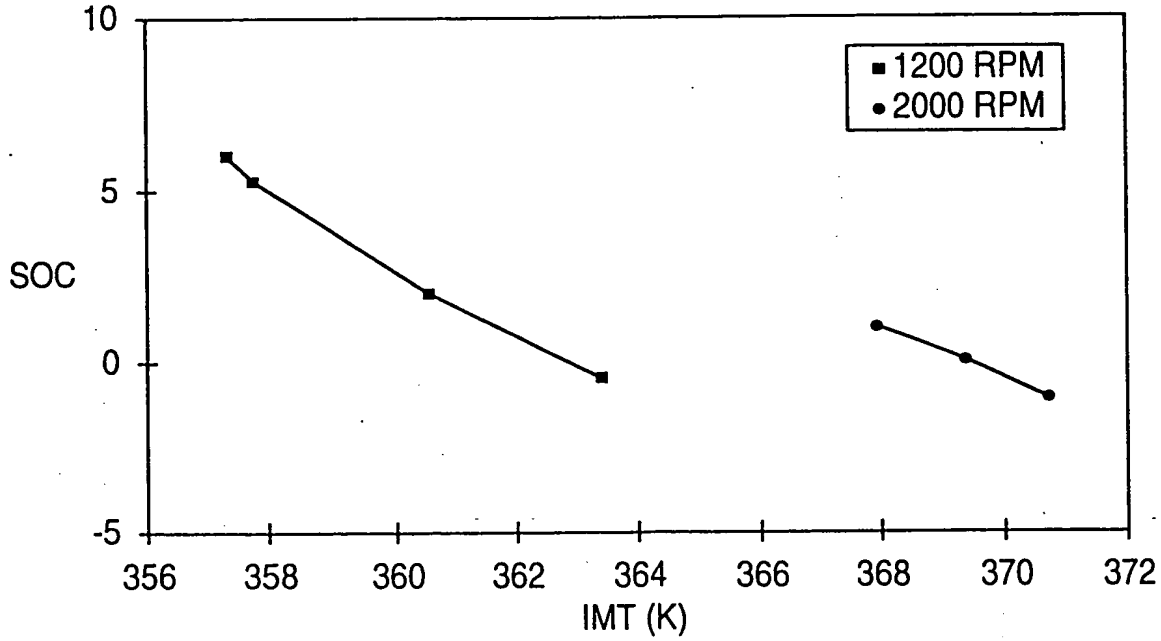

10
5
0
-5
SOC
356
358
360
362
364
366
368
370
372
IMT (K)
1200 RPM
2000 RPM

FIG. 7e

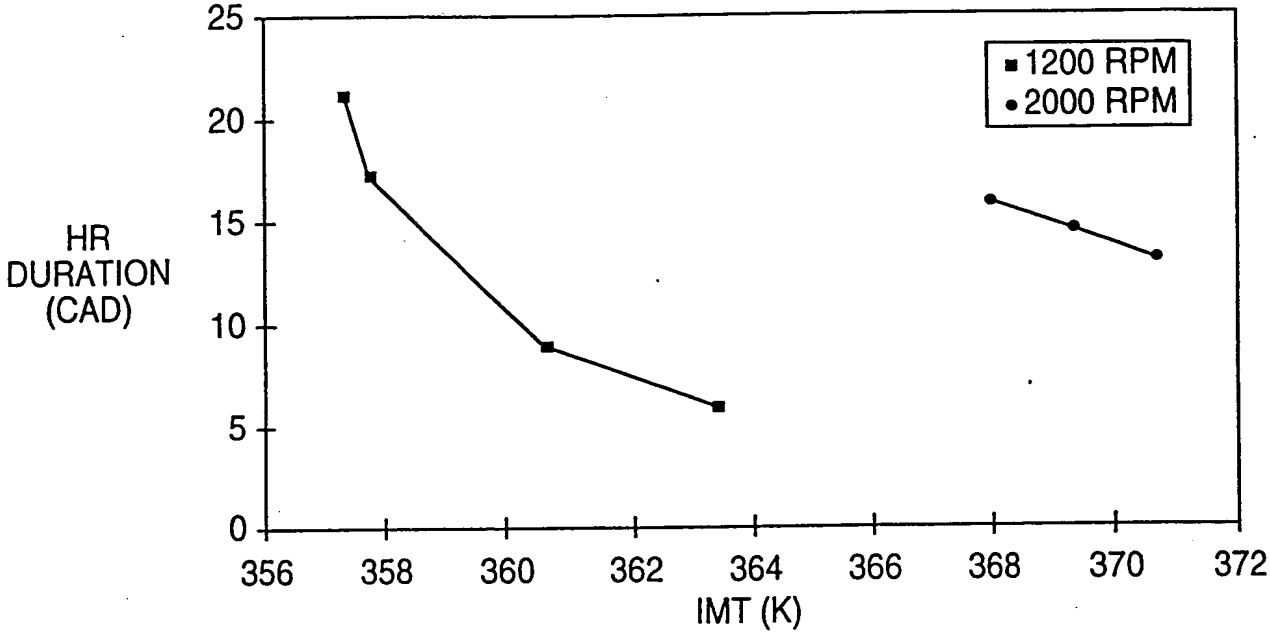

25
20
15
10
5
0
HR
DURATION
(CAD)
356
358
360
362
364
366
368
370
372
IMT (K)
1200 RPM
2000 RPM

FIG. 7f

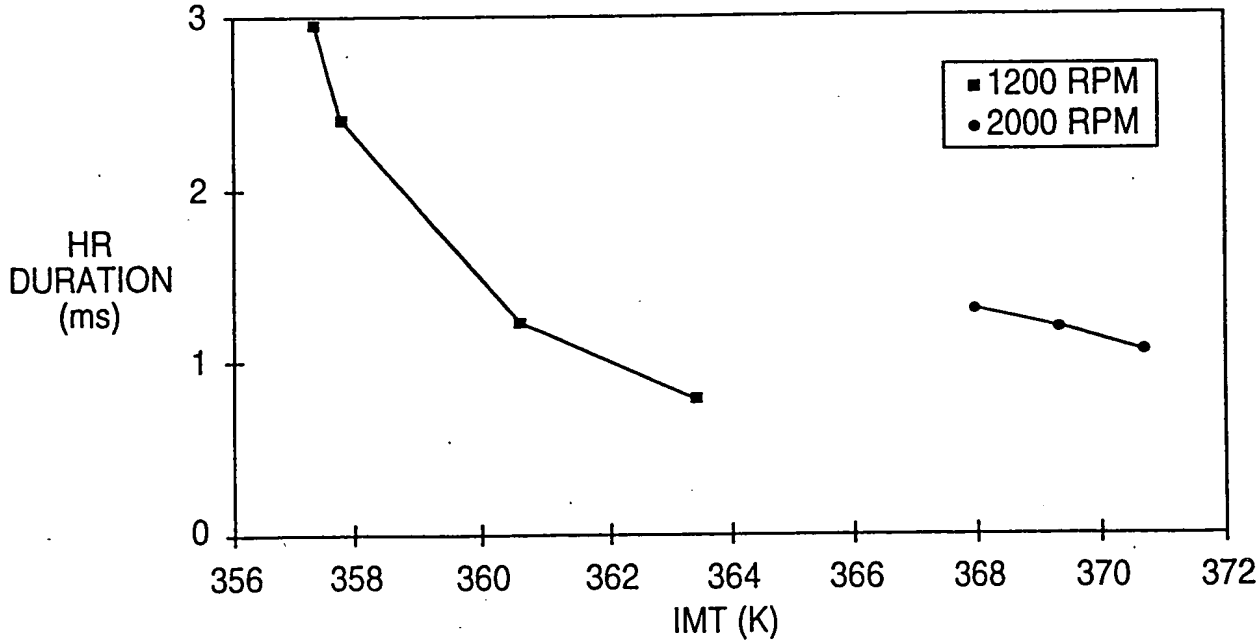

3
2
1
0
HR
DURATION
(ms)
356
358
360
362
364
366
368
370
372
IMT (K)
1200 RPM
2000 RPM

FIG. 7g

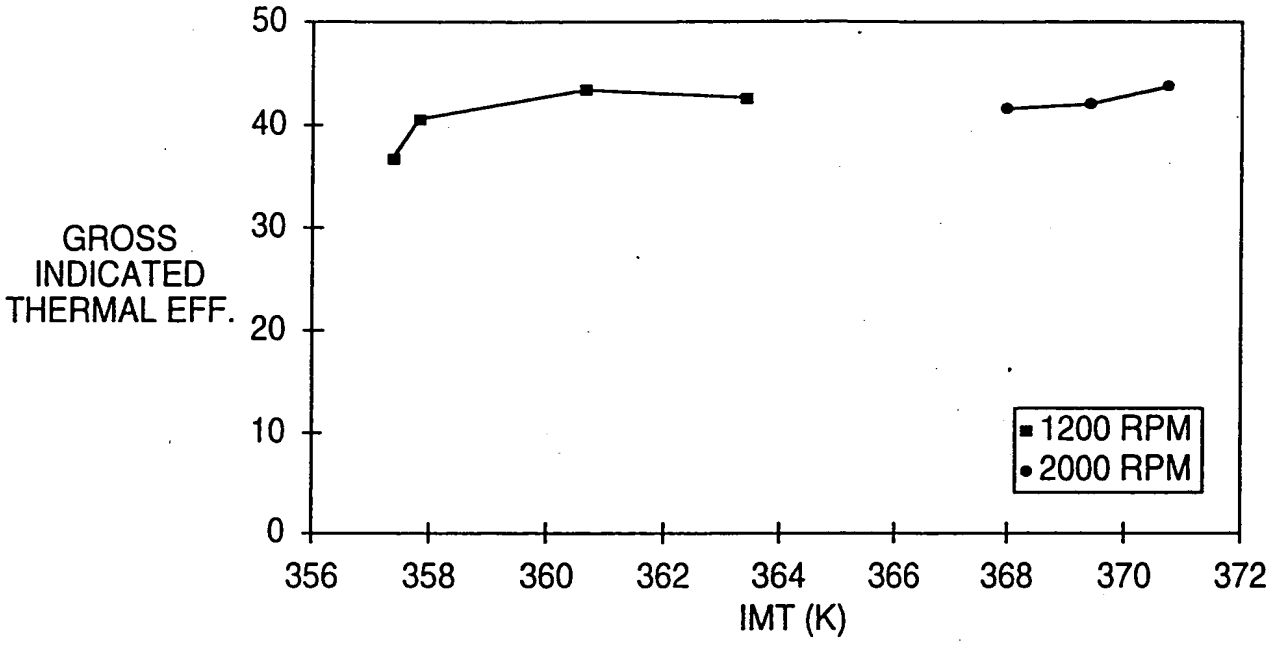

GROSS
INDICATED
THERMAL EFF.
50
40
30
20
10
0
356
358
360
362
364
366
368
370
372
IMT (K)
1200 RPM
2000 RPM

FIG. 7h

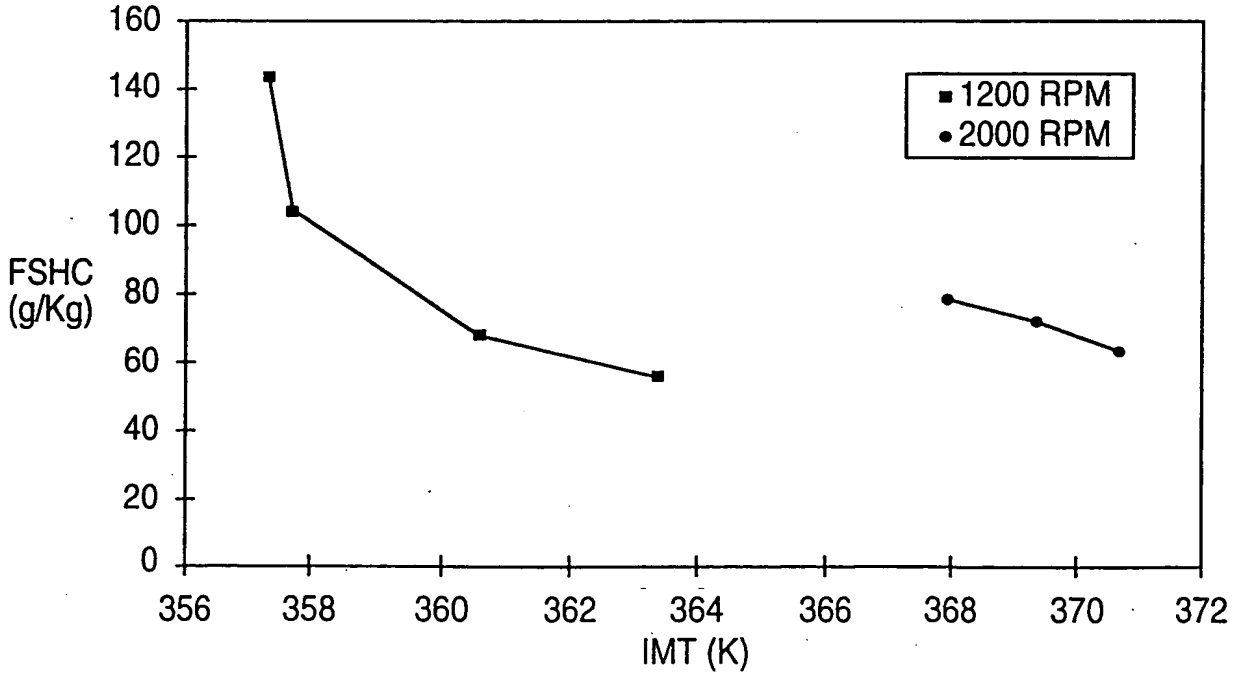

FSHC
(g/Kg)
160
140
120
100
80
60
40
20
0
356
358
360
362
364
366
368
370
372
IMT (K)
1200 RPM
2000 RPM

FIG. 7i

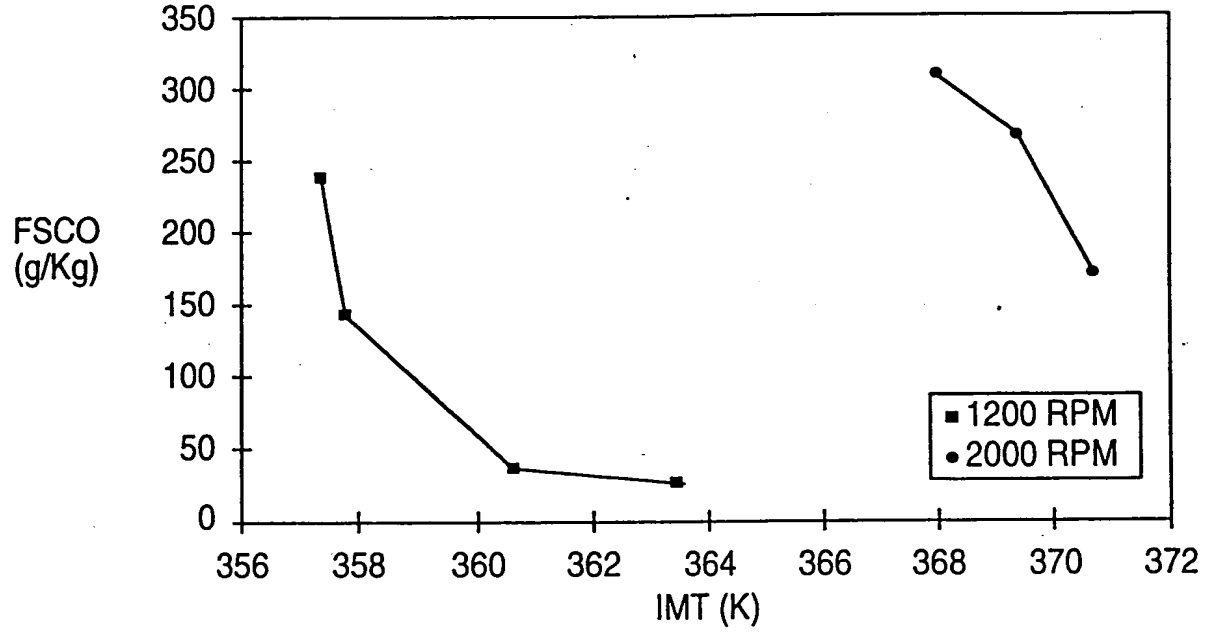

350
300
250
200
150
100
50
0
FSCO
(g/Kg)
1200 RPM
2000 RPM
356
358
360
362
364
366
368
370
372
IMT (K)

FIG. 7j

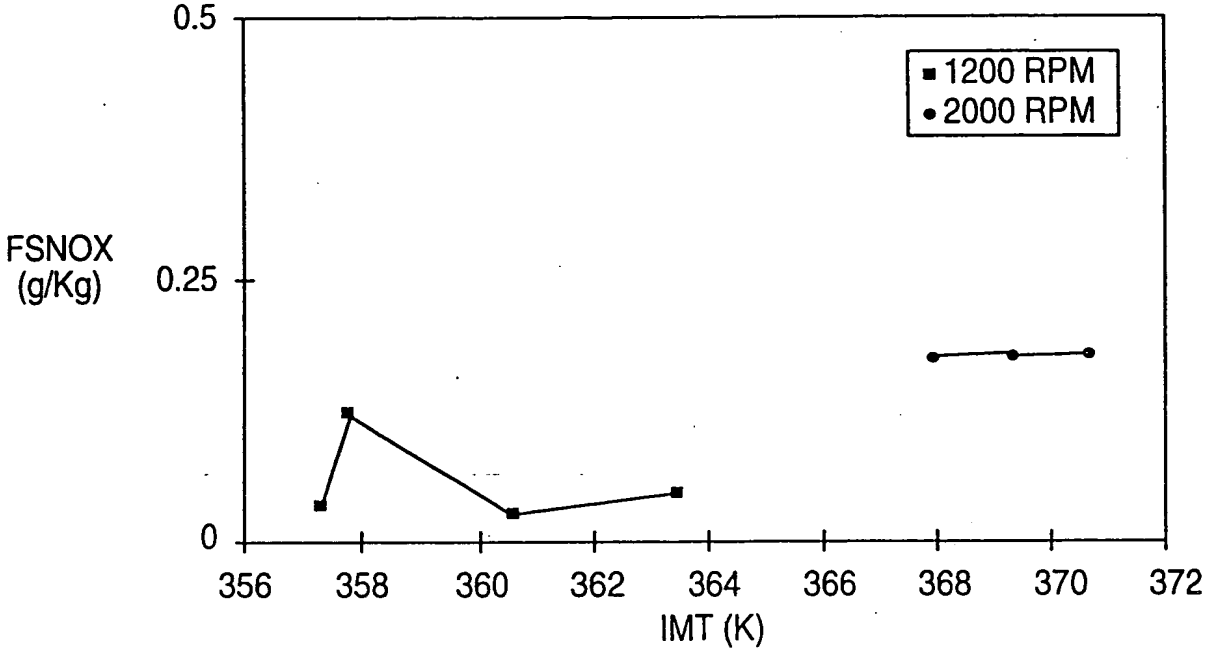

0.5
0.25
0
FSNOX
(g/Kg)
1200 RPM
2000 RPM
356
358
360
362
364
366
368
370
372
IMT (K)

FIG. 7k

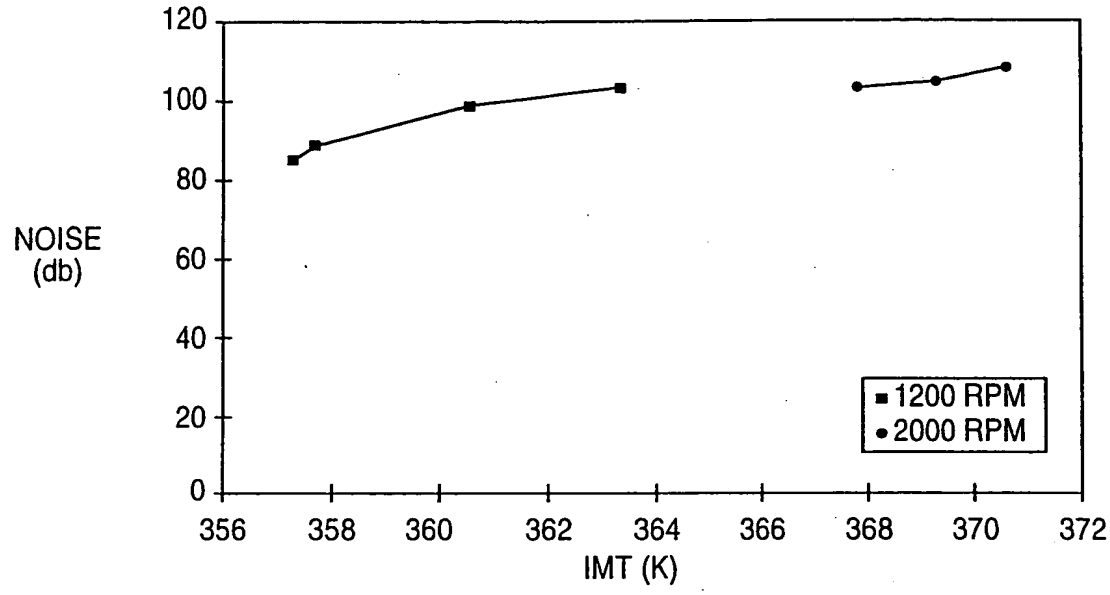

120
100
80
60
40
20
0
NOISE
(db)
356
358
360
362
364
366
368
370
372
IMT (K)
1200 RPM
2000 RPM

FIG. 8

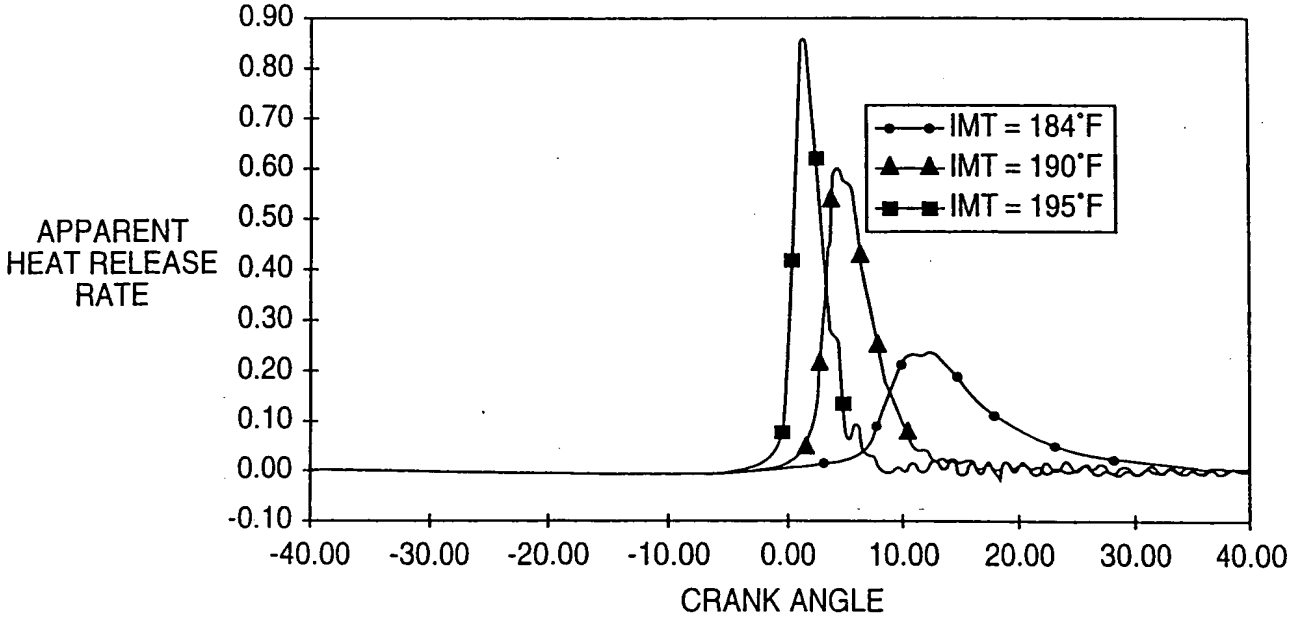

0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
APPARENT
HEAT RELEASE
RATE
-40.00
-30.00
-20.00
-10.00
0.00
10.00
20.00
30.00
40.00
CRANK ANGLE
IMT = 184°F
IMT = 190°F
IMT = 195°F

FIG. 9

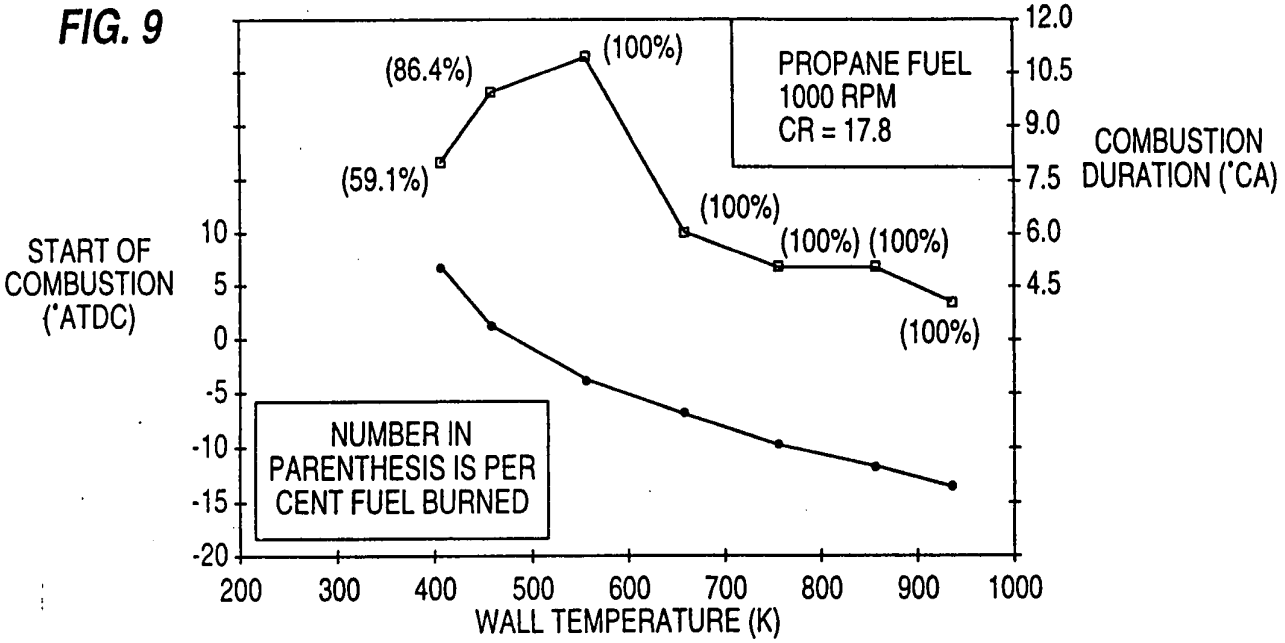

PROPANE FUEL
1000 RPM
CR = 17.8
(86.4%)
(100%)
(59.1%)
(100%)
(100%)
(100%)
(100%)
NUMBER IN PARENTHESIS IS PER CENT FUEL BURNED
START OF COMBUSTION (°ATDC)
COMBUSTION DURATION (°CA)
WALL TEMPERATURE (K)
12.0
10.5
9.0
7.5
6.0
4.5
10
5
0
-5
-10
-15
-20
200
300
400
500
600
700
800
900
1000

FIG. 10

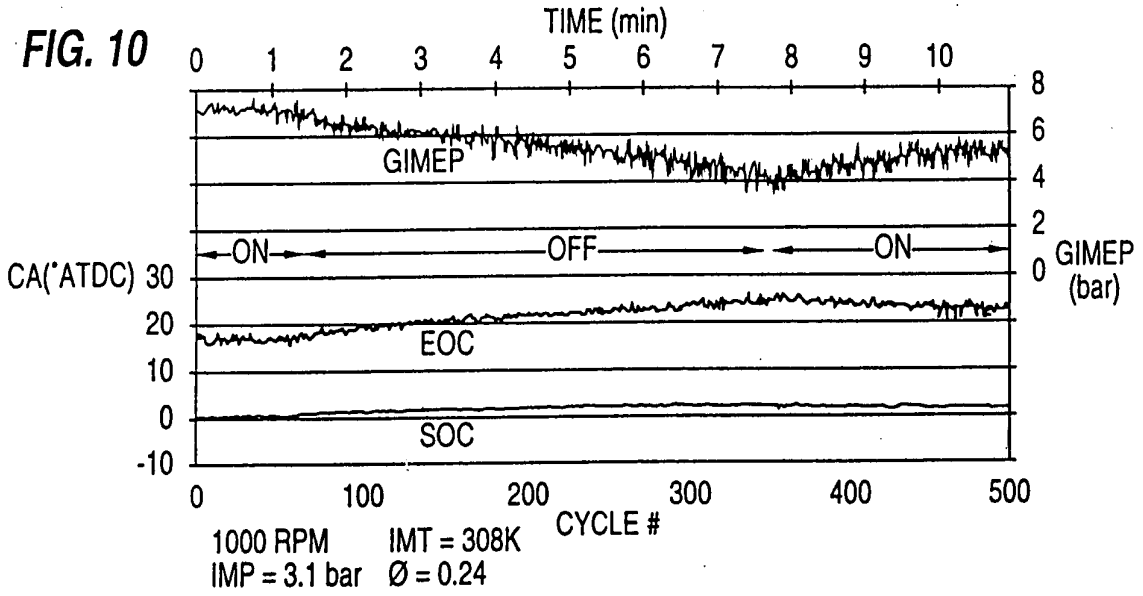

TIME (min)
0
1
2
3
4
5
6
7
8
9
10
GIMEP
ON
OFF
ON
CA(°ATDC)
EOC
SOC
GIMEP (bar)
8
6
4
2
0
30
20
10
0
-10
0
100
200
300
400
500
CYCLE #
1000 RPM
IMT = 308K
IMP = 3.1 bar
Ø = 0.24

FIG. 11

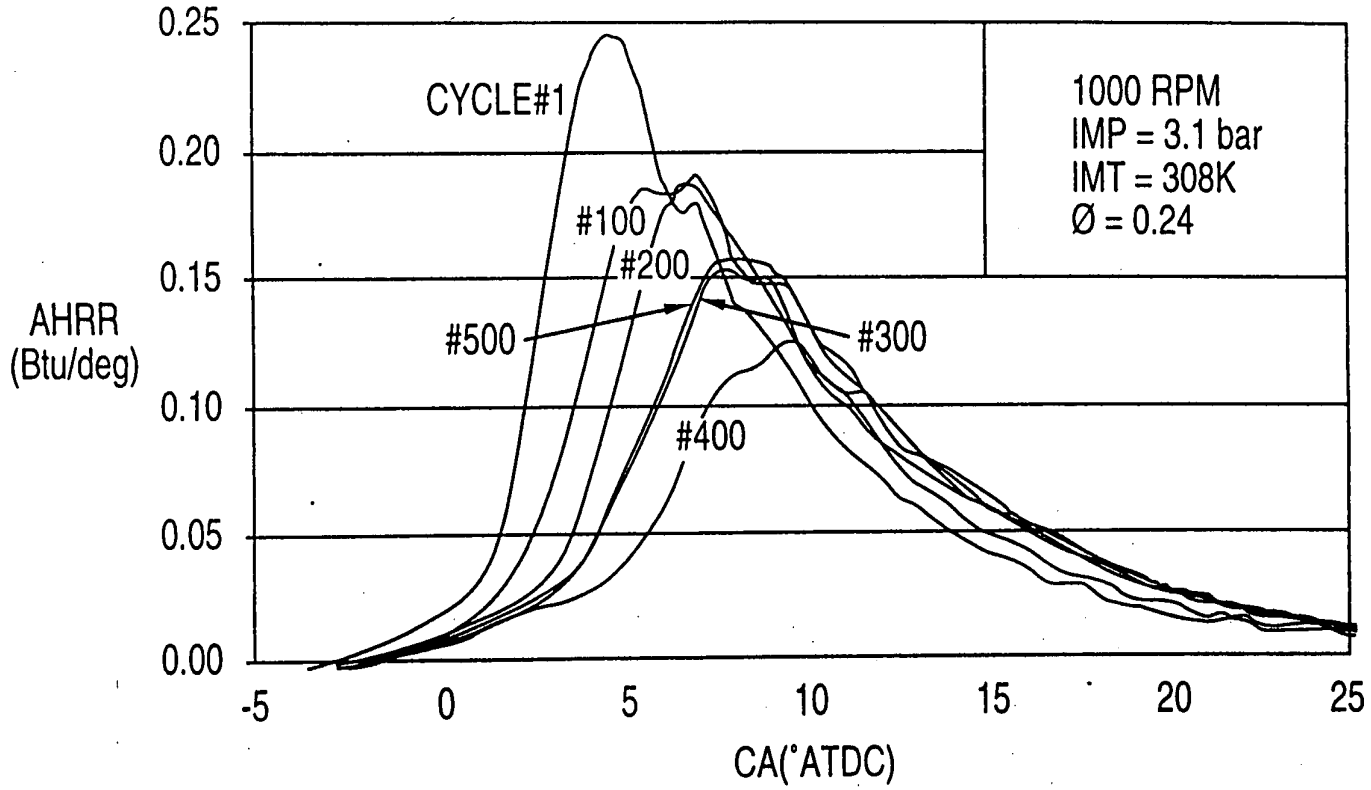

0.25
0.20
0.15
0.10
0.05
0.00
AHRR
(Btu/deg)
CYCLE#1
#100
#200
#500
#300
#400
1000 RPM
IMP = 3.1 bar
IMT = 308K
Ø = 0.24
-5
0
5
10
15
20
25
CA(˚ATDC)

FIG. 12

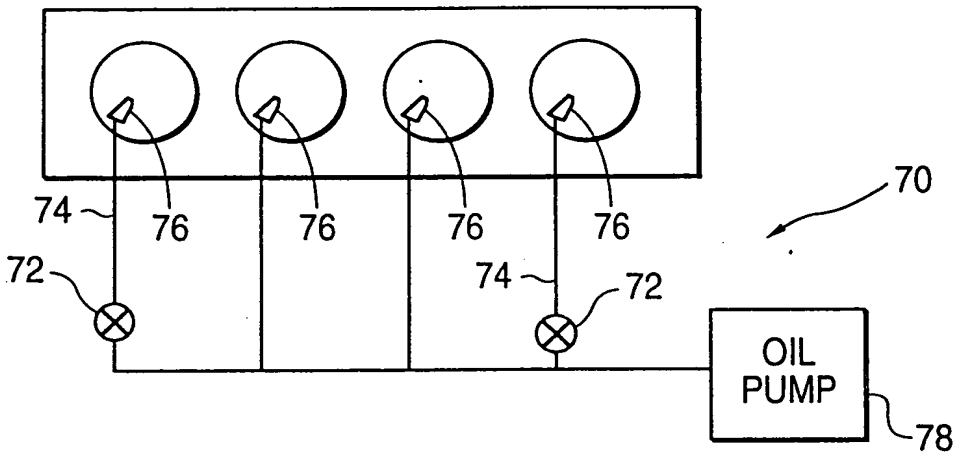

74
76
76
76
76
70
72
74
72
OIL
PUMP
78

FIG. 13

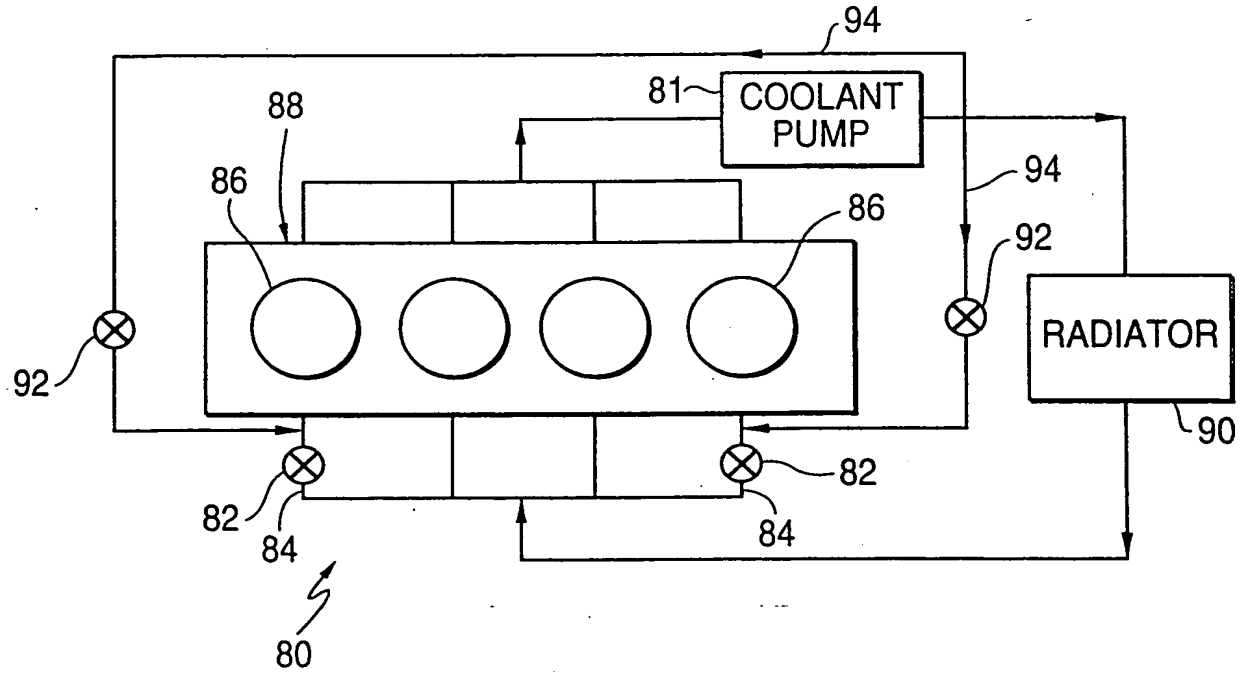

94
81
COOLANT
PUMP
88
86
86
94
92
92
RADIATOR
90
82
82
84
84
80

FIG. 14

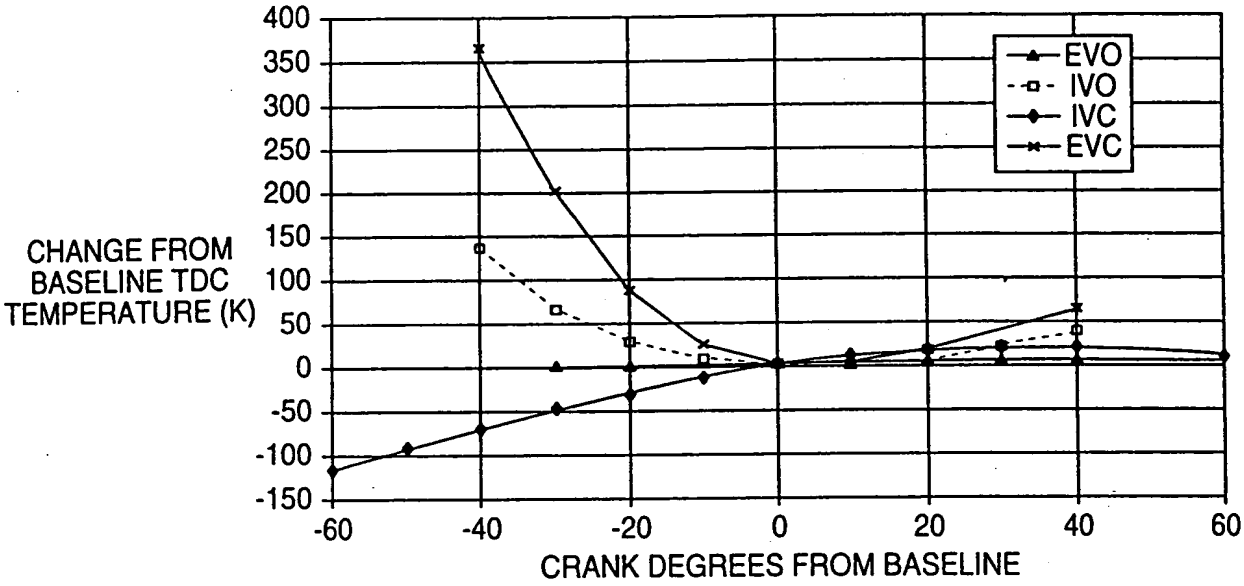

400
350
300
250
200
150
100
50
0
-50
-100
-150
-60
-40
-20
0
20
40
60
EVO
IVO
IVC
EVC
CHANGE FROM BASELINE TDC TEMPERATURE (K)
CRANK DEGREES FROM BASELINE

FIG. 15

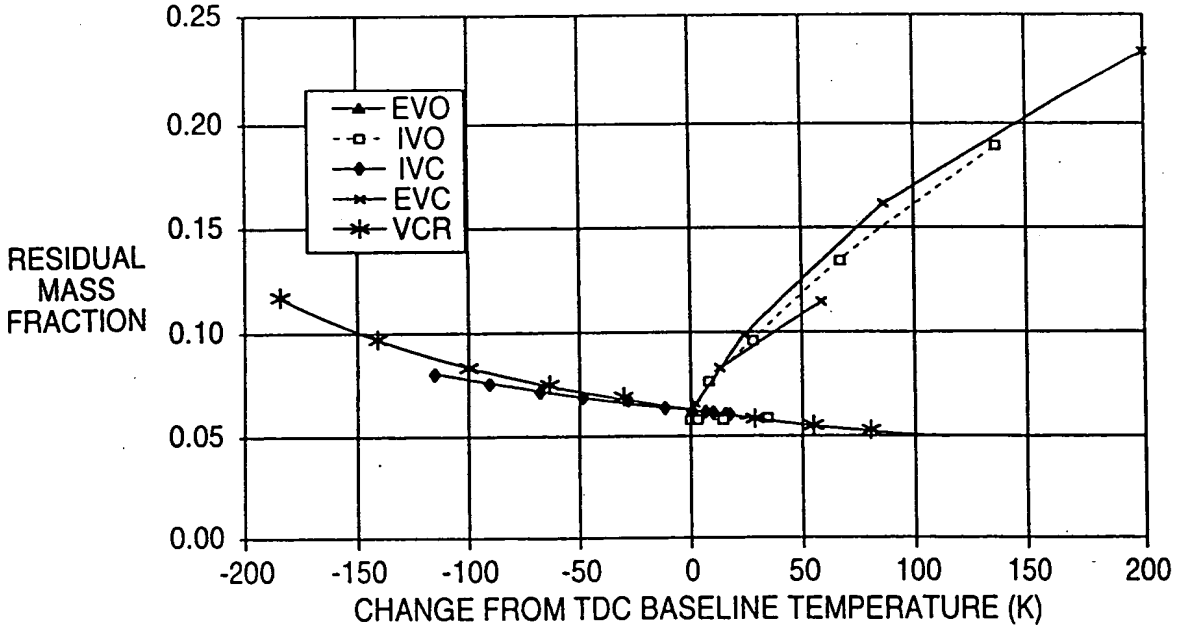

0.25
0.20
0.15
0.10
0.05
0.00
-200
-150
-100
-50
0
50
100
150
200
EVO
IVO
IVC
EVC
VCR
RESIDUAL MASS FRACTION
CHANGE FROM TDC BASELINE TEMPERATURE (K)

FIG. 16

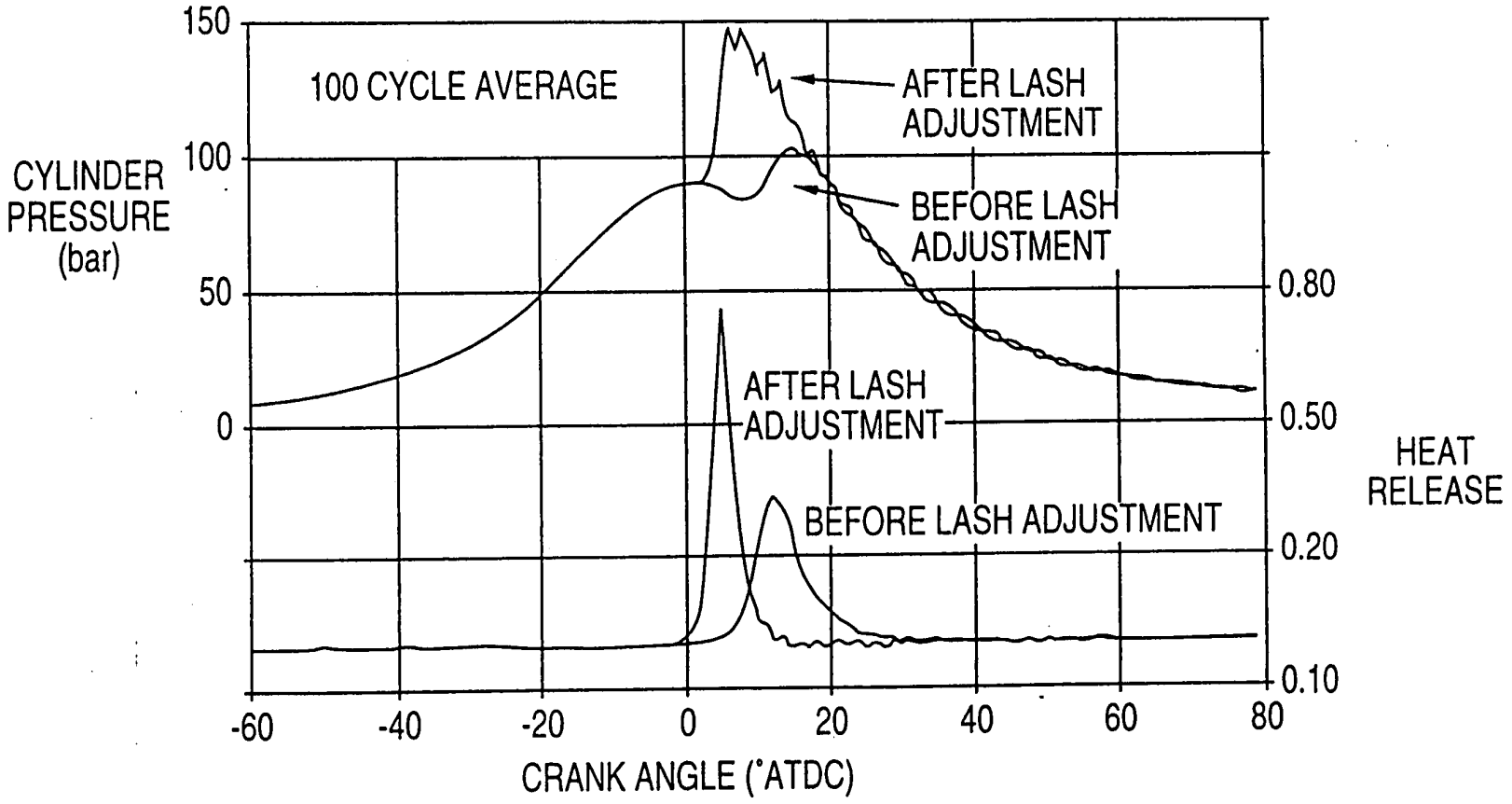

150
100
50
0
100 CYCLE AVERAGE
AFTER LASH ADJUSTMENT
BEFORE LASH ADJUSTMENT
AFTER LASH ADJUSTMENT
BEFORE LASH ADJUSTMENT
CYLINDER PRESSURE (bar)
0.80
0.50
0.20
0.10
HEAT RELEASE
-60
-40
-20
0
20
40
60
80
CRANK ANGLE (°ATDC)

FIG. 17

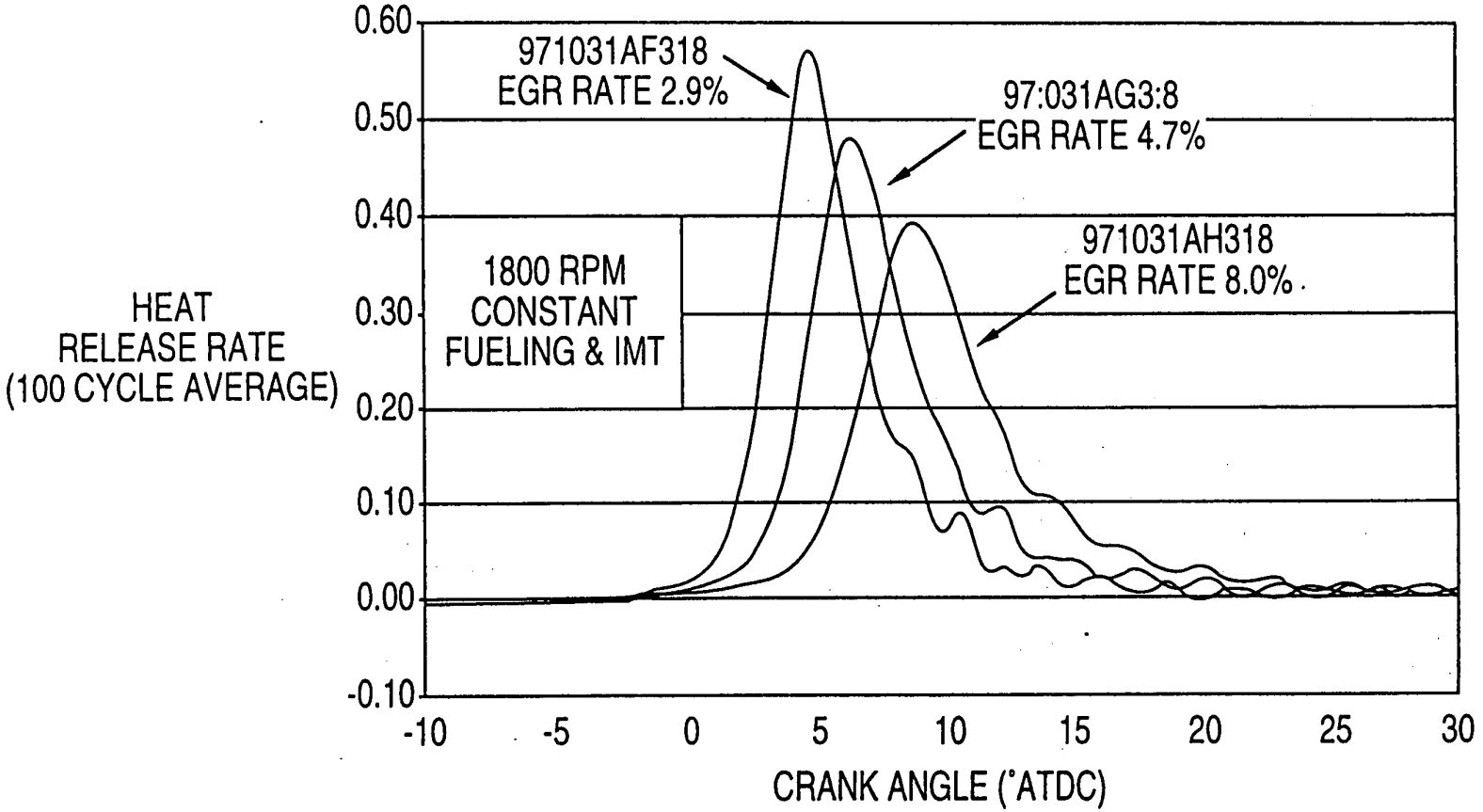

0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
971031AF318
EGR RATE 2.9%
97:031AG3:8
EGR RATE 4.7%
971031AH318
EGR RATE 8.0%
1800 RPM
CONSTANT
FUELING & IMT
HEAT
RELEASE RATE
(100 CYCLE AVERAGE)
-10
-5
0
5
10
15
20
25
30
CRANK ANGLE (°ATDC)

FIG. 18

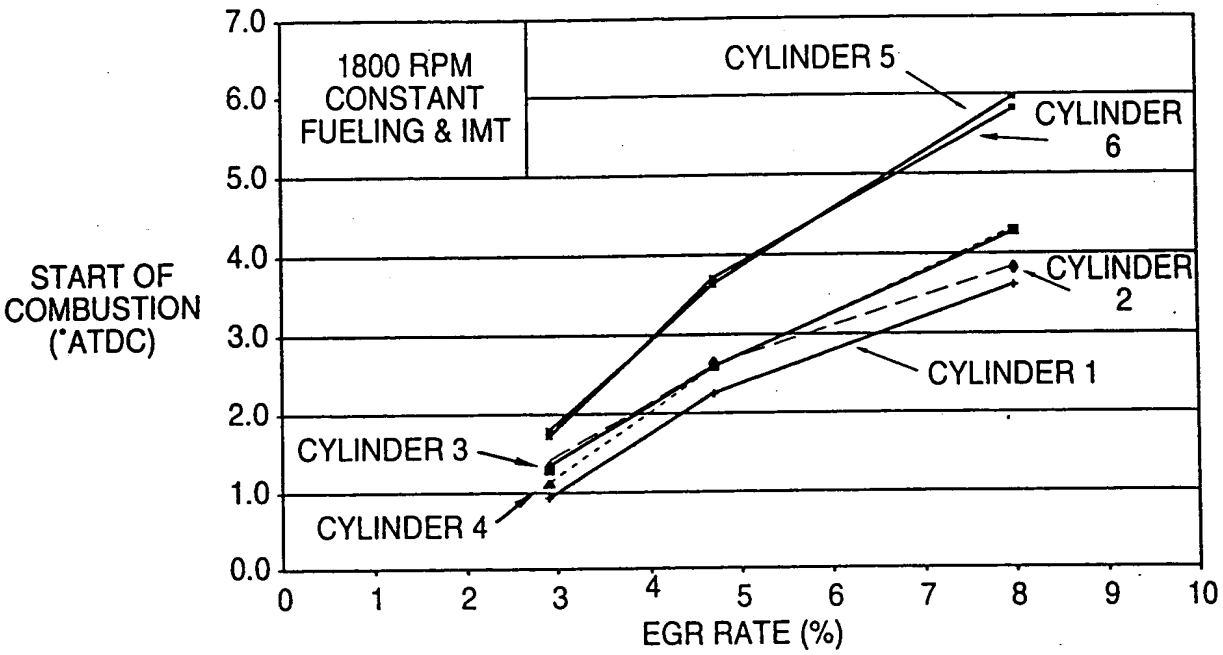

7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1800 RPM
CONSTANT
FUELING & IMT
CYLINDER 5
CYLINDER
6
CYLINDER
2
CYLINDER 1
CYLINDER 3
CYLINDER 4
START OF
COMBUSTION
(°ATDC)
0
1
2
3
4
5
6
7
8
9
10
EGR RATE (%)

FIG. 19

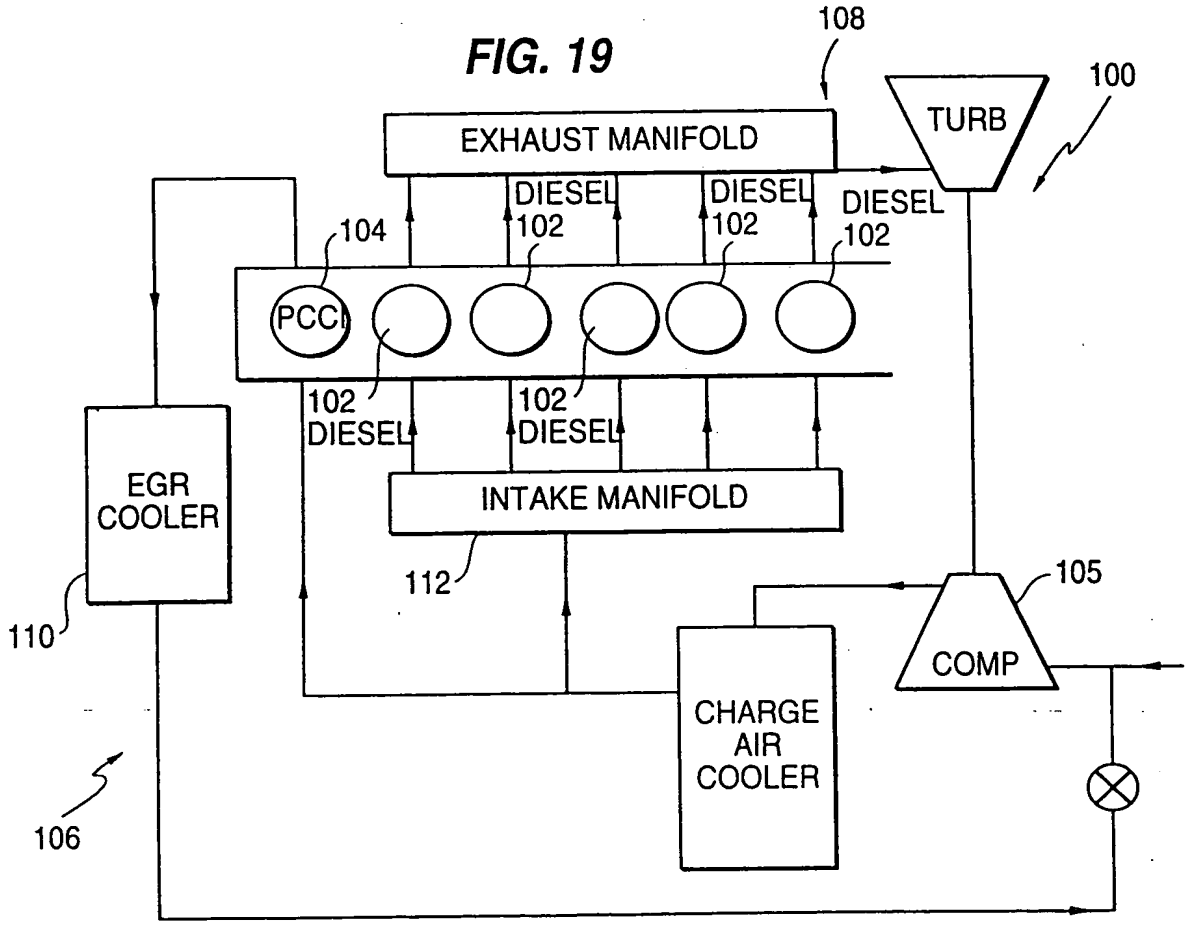

108
100
TURB
EXHAUST MANIFOLD
DIESEL
102
DIESEL
102
DIESEL
102
104
PCC
102
DIESEL
102
DIESEL
EGR
COOLER
INTAKE MANIFOLD
112
105
COMP
110
CHARGE
AIR
COOLER
106

FIG. 20

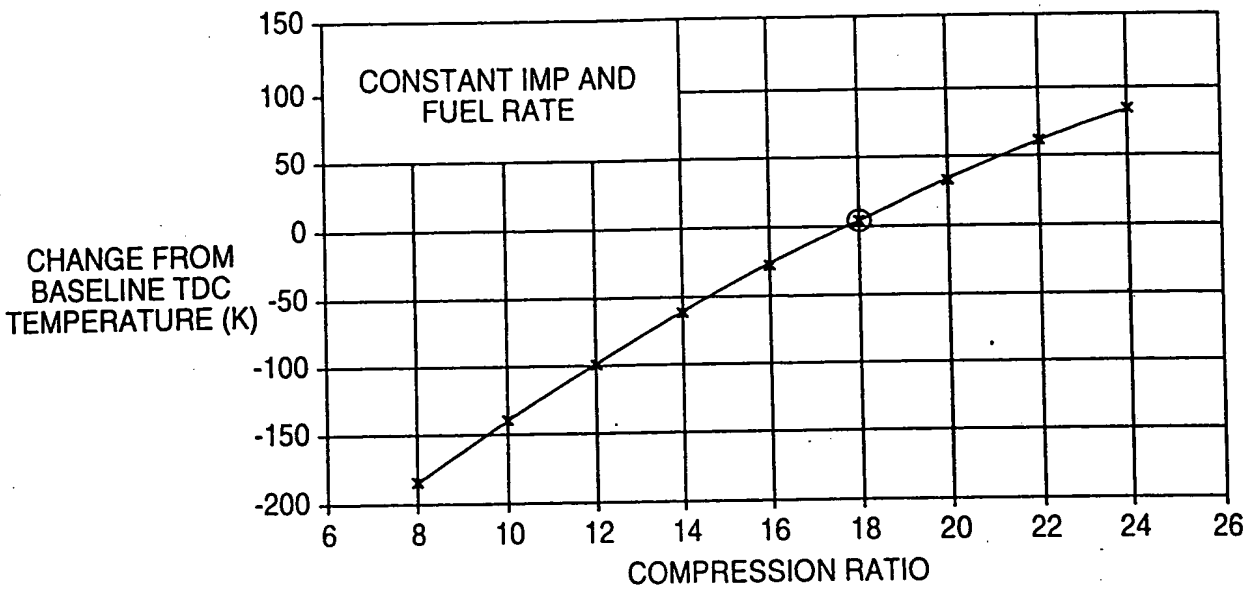
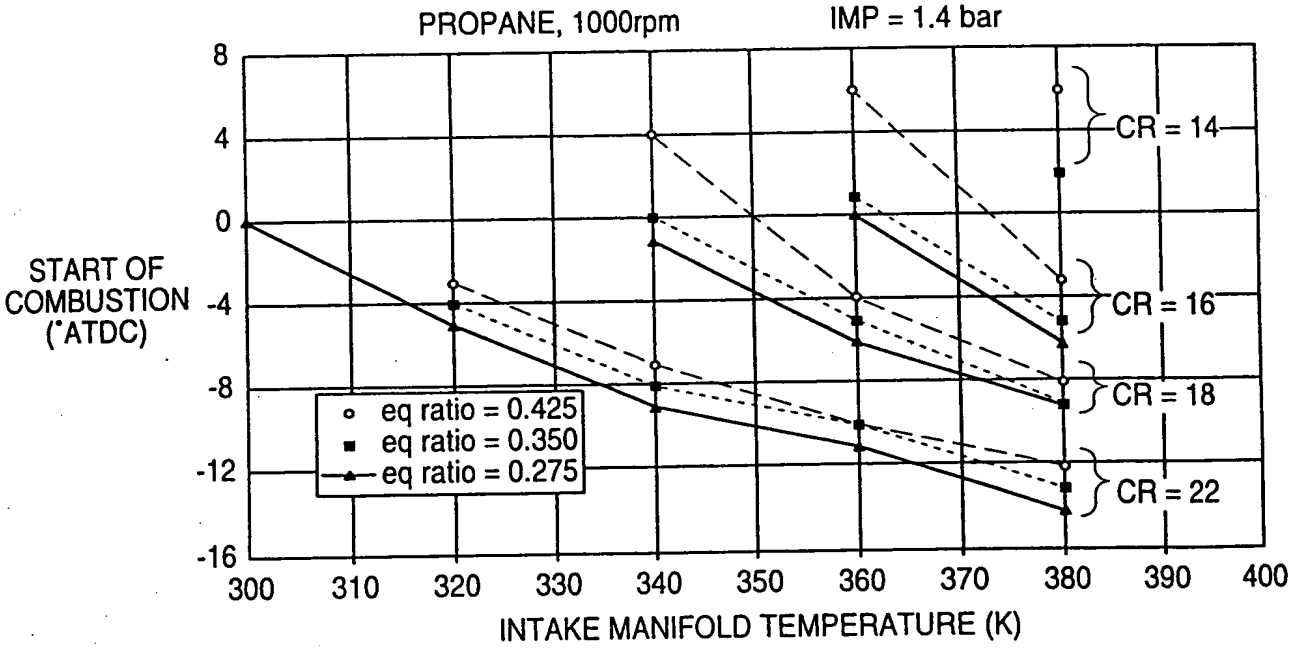

CONSTANT IMP AND FUEL RATE
CHANGE FROM BASELINE TDC TEMPERATURE (K)
150
100
50
0
-50
-100
-150
-200
6
8
10
12
14
16
18
20
22
24
26
COMPRESSION RATIO

FIG. 21


PROPANE, 1000rpm
IMP = 1.4 bar
START OF COMBUSTION (°ATDC)
8
4
0
-4
-8
-12
-16
eq ratio = 0.425
eq ratio = 0.350
eq ratio = 0.275
CR = 14
CR = 16
CR = 18
CR = 22
300
310
320
330
340
350
360
370
380
390
400
INTAKE MANIFOLD TEMPERATURE (K)

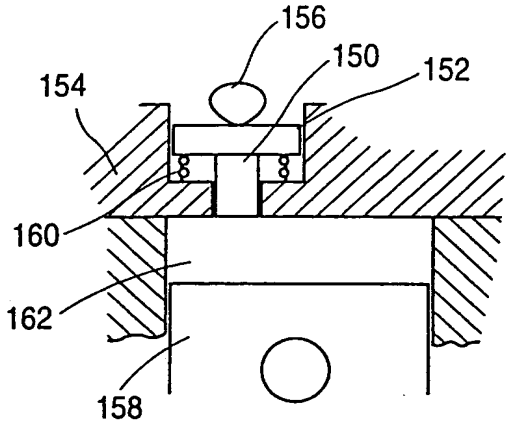


FIG. 22a

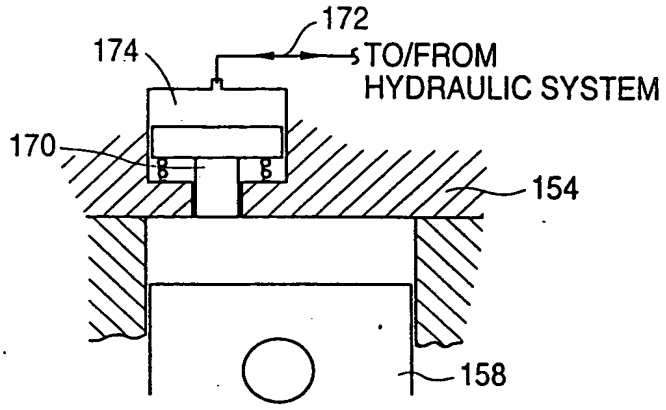


FIG. 22b

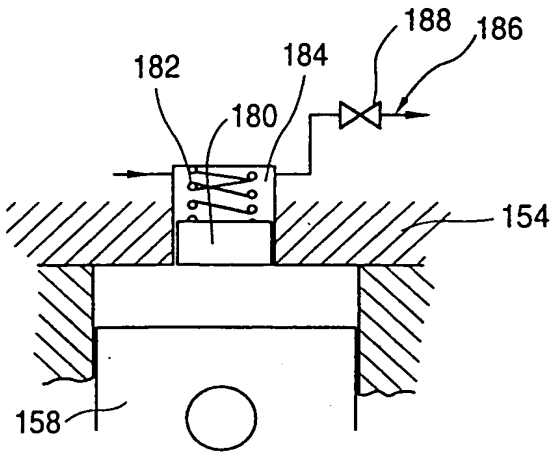


FIG. 22c

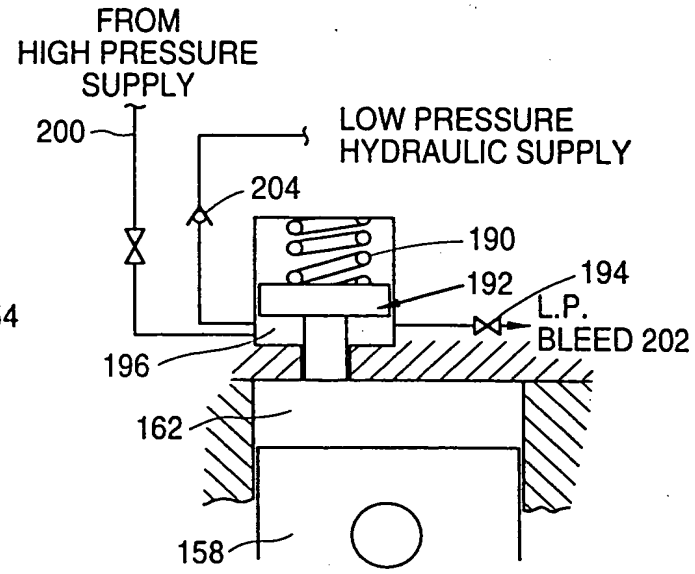


FIG. 22d

FIG. 23

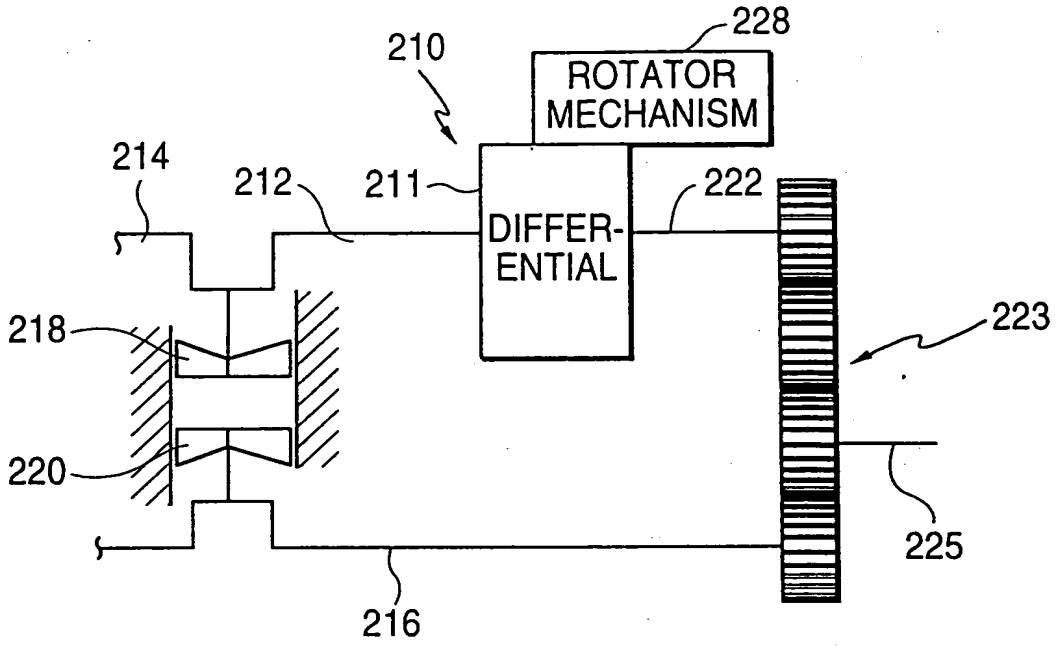

228
210
ROTATOR MECHANISM
214
212
211
DIFFER-ENTIAL
222
223
218
220
225
216

FIG. 24

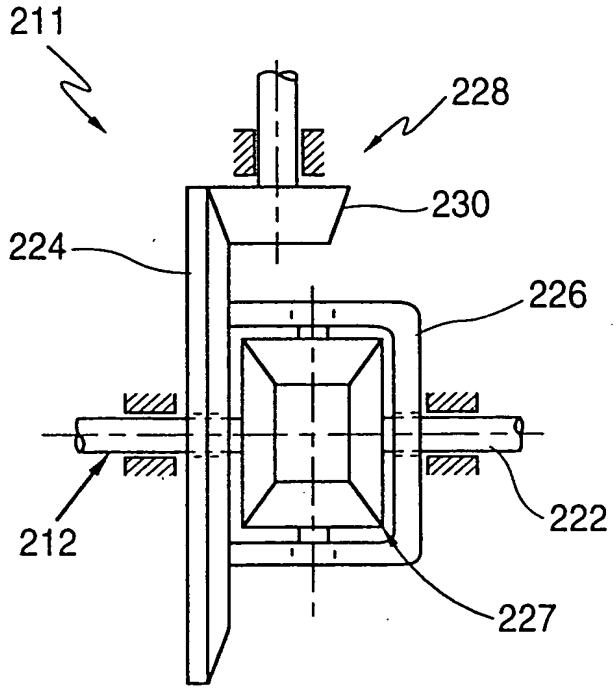

211
228
230
224
226
212
222
227

FIG. 25

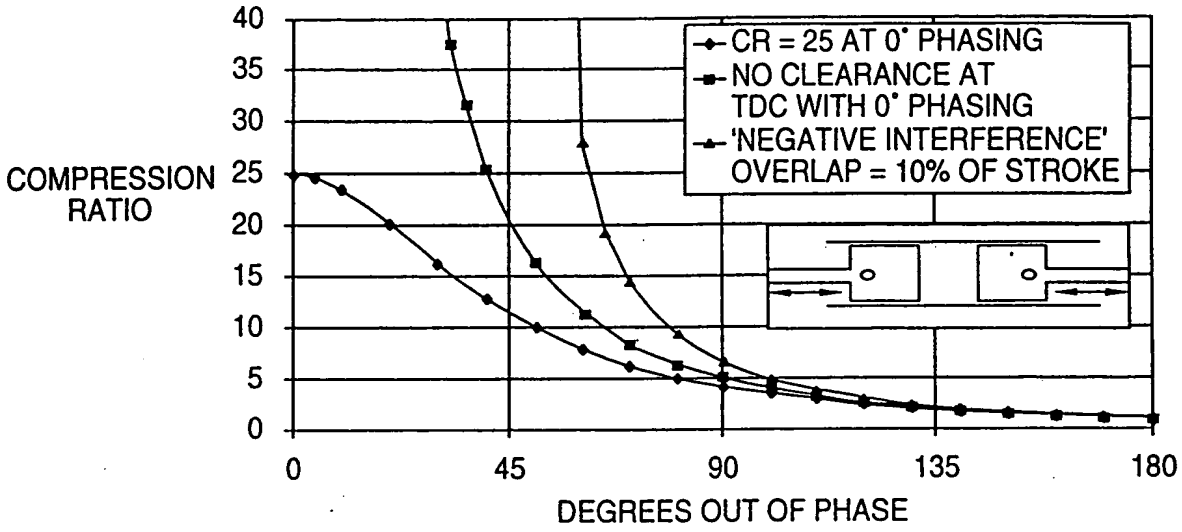

COMPRESSION RATIO
40
35
30
25
20
15
10
5
0
0
45
90
135
180
DEGREES OUT OF PHASE
CR = 25 AT 0° PHASING
NO CLEARANCE AT TDC WITH 0° PHASING
'NEGATIVE INTERFERENCE' OVERLAP = 10% OF STROKE

FIG. 26

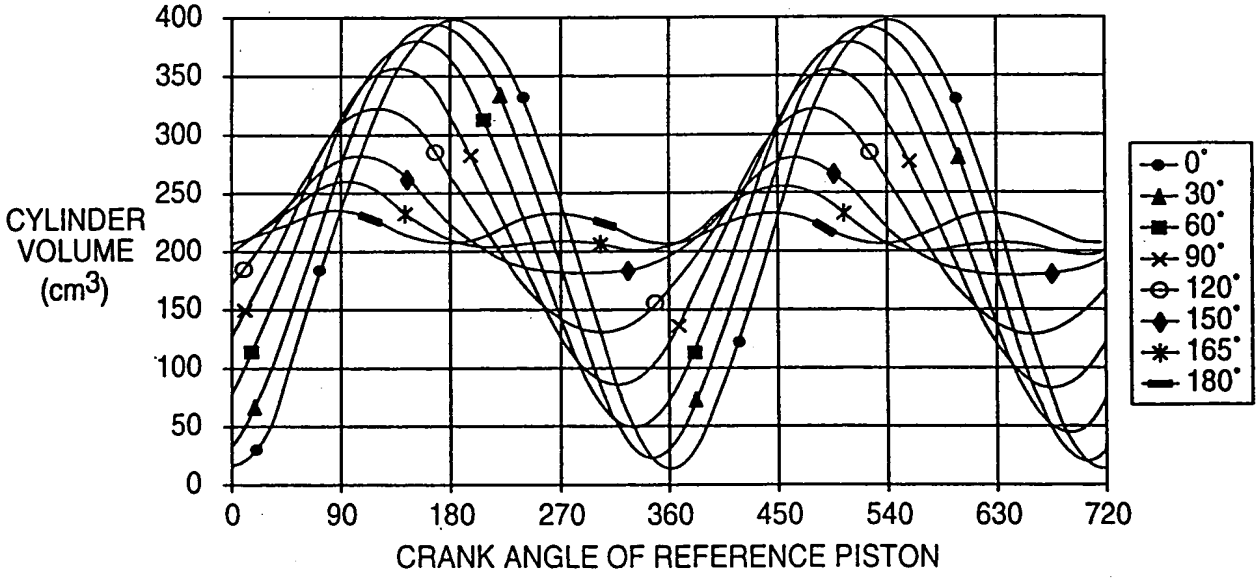

CYLINDER VOLUME (cm^3)
400
350
300
250
200
150
100
50
0
0
90
180
270
360
450
540
630
720
CRANK ANGLE OF REFERENCE PISTON
0°
30°
60°
90°
120°
150°
165°
180°

FIG. 27

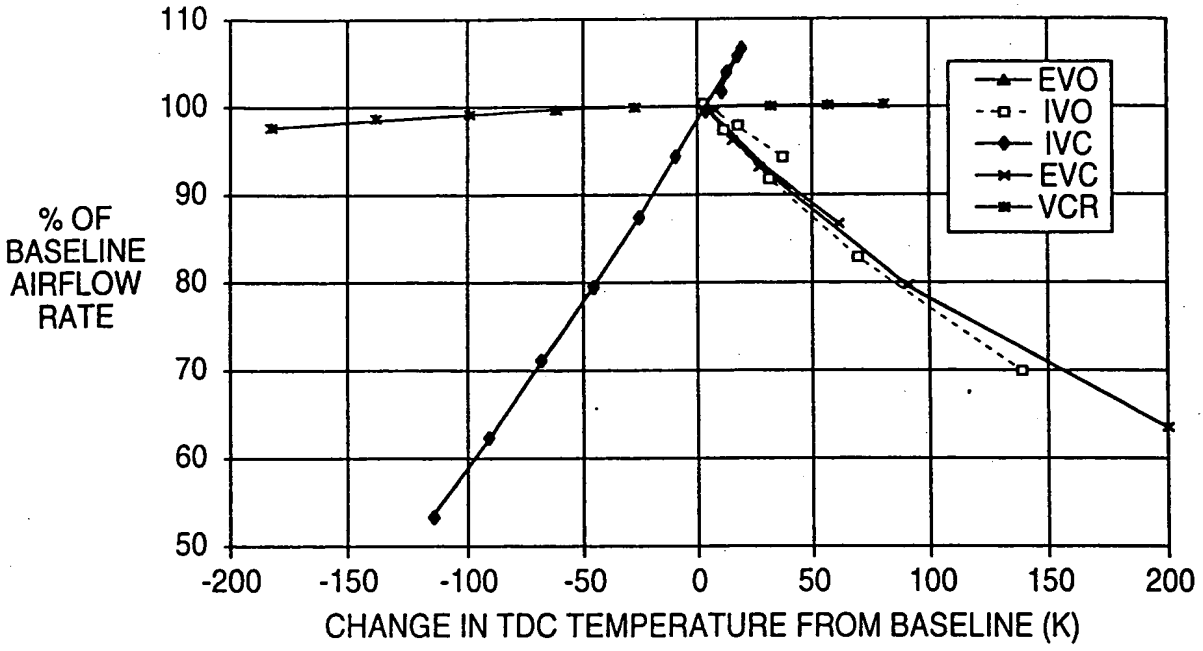

110
100
90
80
70
60
50
% OF BASELINE AIRFLOW RATE
-200
-150
-100
-50
0
50
100
150
200
CHANGE IN TDC TEMPERATURE FROM BASELINE (K)
EVO
IVO
IVC
EVC
VCR

FIG. 28

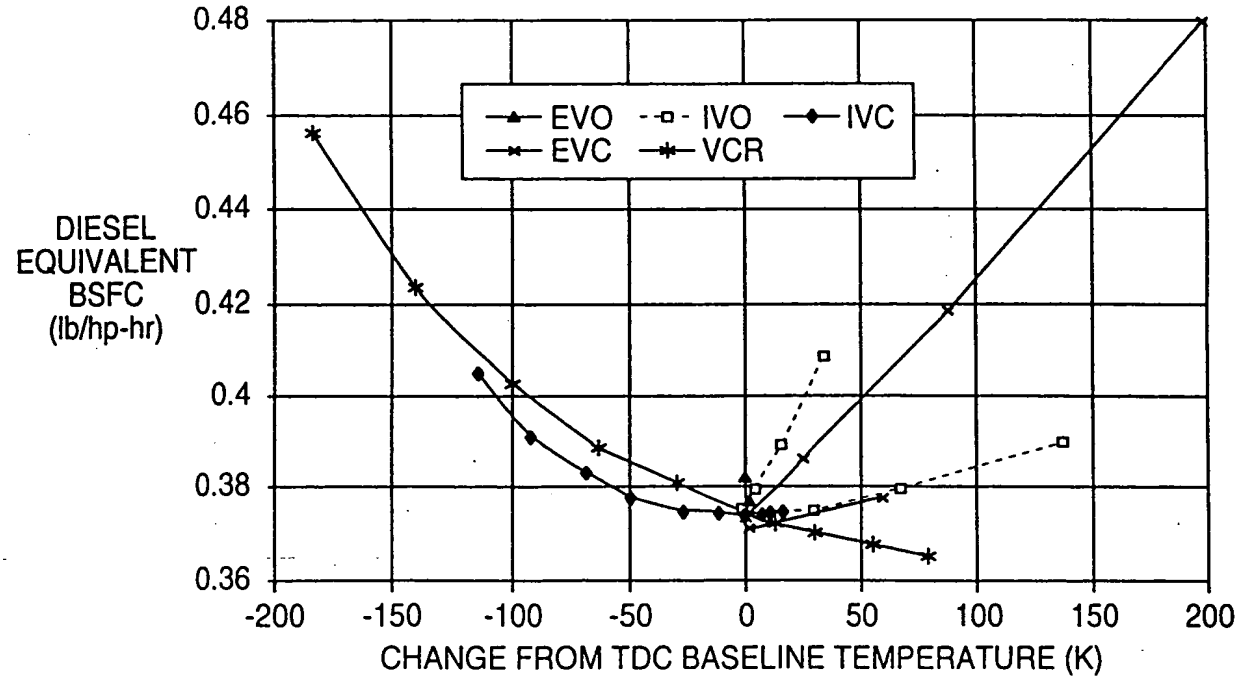

0.48
0.46
0.44
0.42
0.4
0.38
0.36
DIESEL EQUIVALENT BSFC (lb/hp-hr)
-200
-150
-100
-50
0
50
100
150
200
CHANGE FROM TDC BASELINE TEMPERATURE (K)
EVO
IVO
IVC
EVC
VCR

FIG. 29

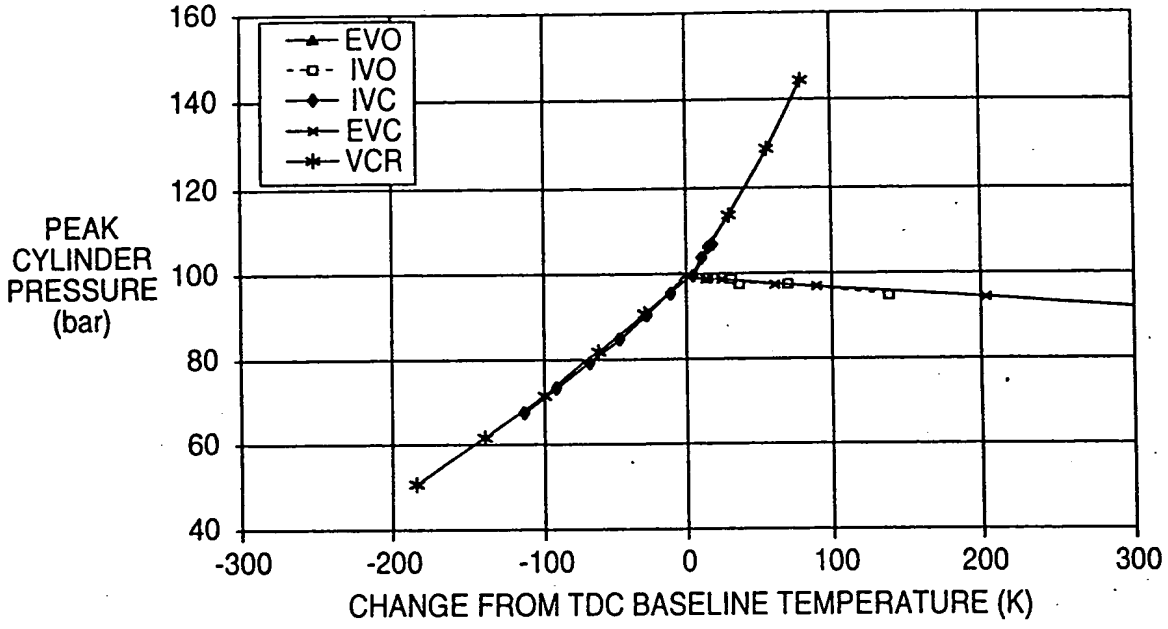

160
140
120
100
80
60
40
EVO
IVO
IVC
EVC
VCR
PEAK CYLINDER PRESSURE (bar)
-300
-200
-100
0
100
200
300
CHANGE FROM TDC BASELINE TEMPERATURE (K)

FIG. 30

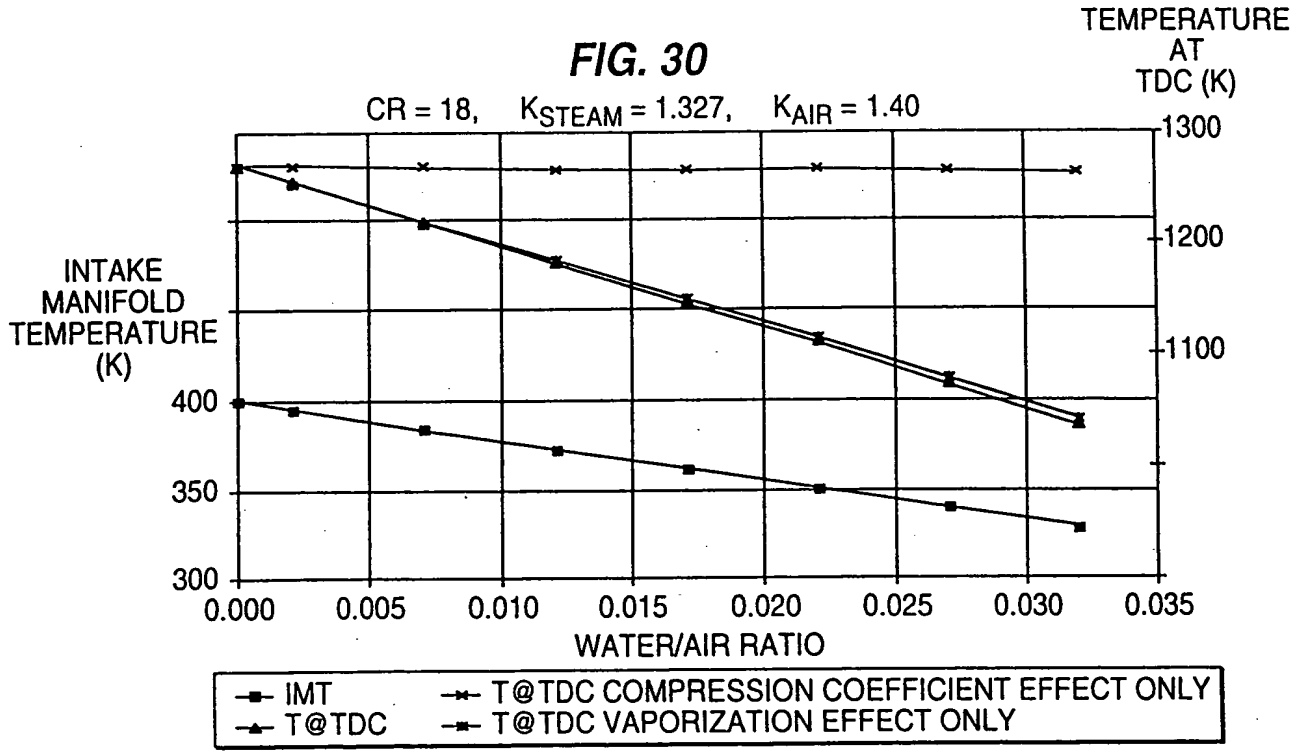

CR = 18, K_{STEAM} = 1.327, K_{AIR} = 1.40
TEMPERATURE AT TDC (K)
1300
1200
1100
INTAKE MANIFOLD TEMPERATURE (K)
400
350
300
0.000
0.005
0.010
0.015
0.020
0.025
0.030
0.035
WATER/AIR RATIO
IMT
T@TDC
T@TDC COMPRESSION COEFFICIENT EFFECT ONLY
T@TDC VAPORIZATION EFFECT ONLY

FIG. 31a

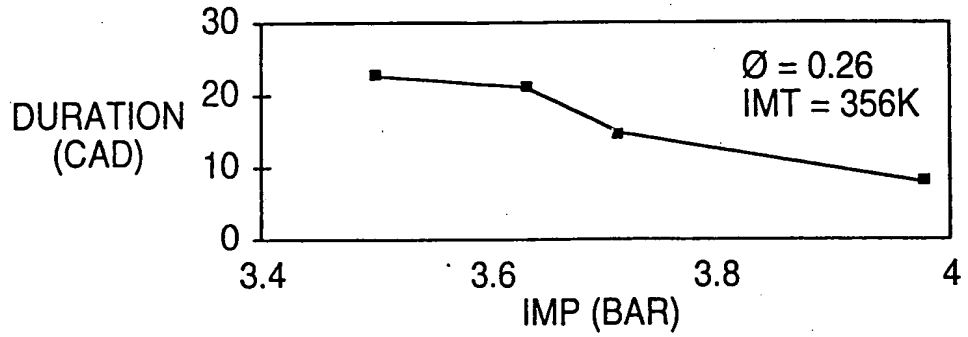


FIG. 31b

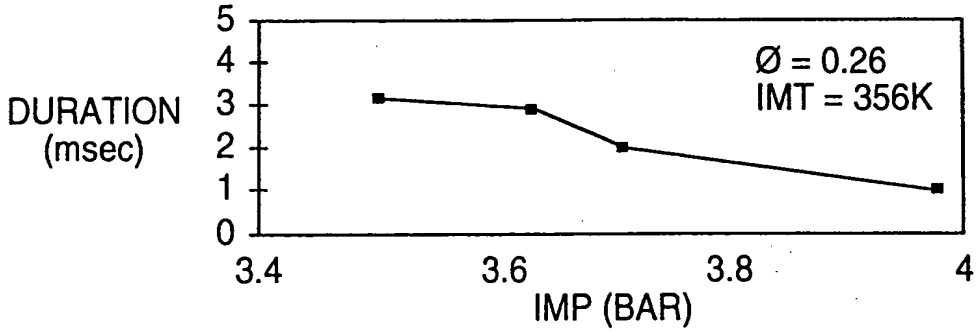
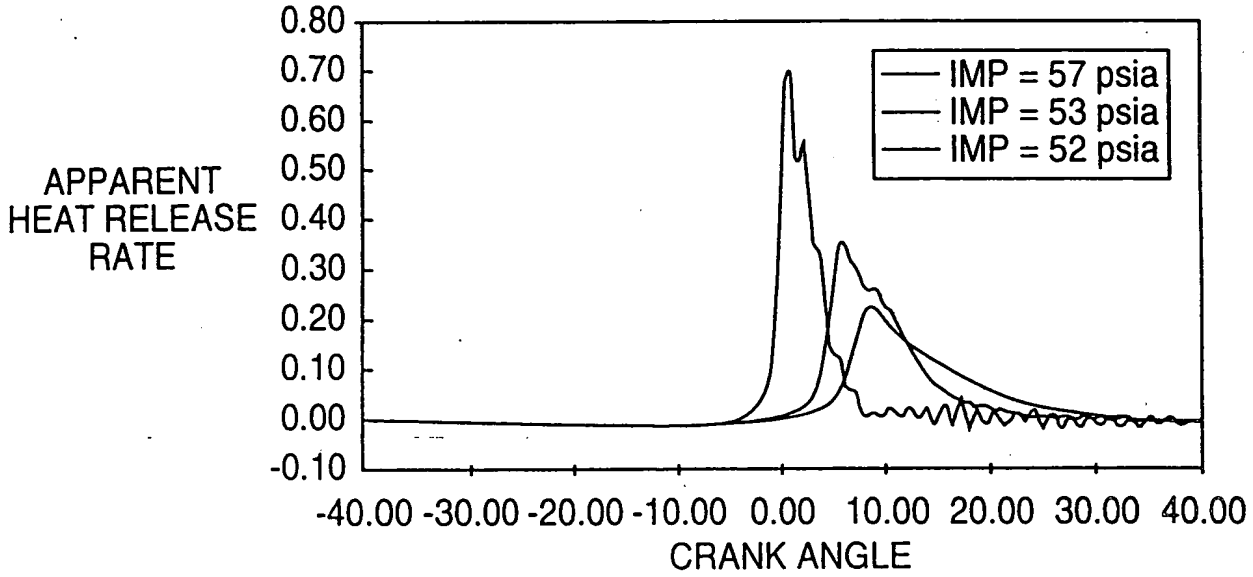


FIG. 31c



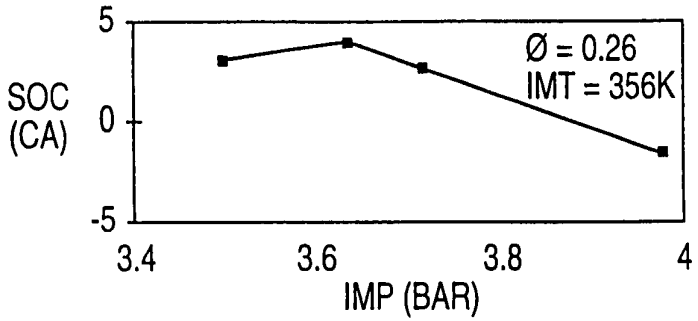


FIG. 31d

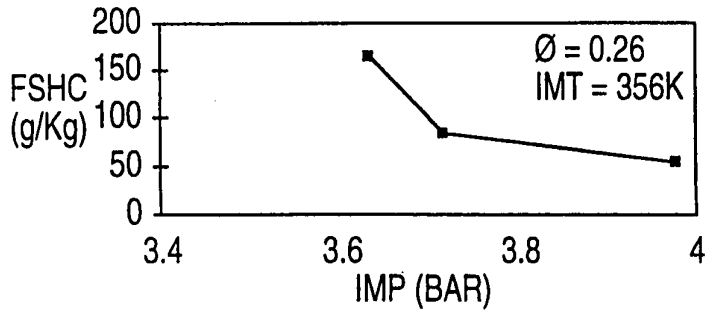


FIG. 31e

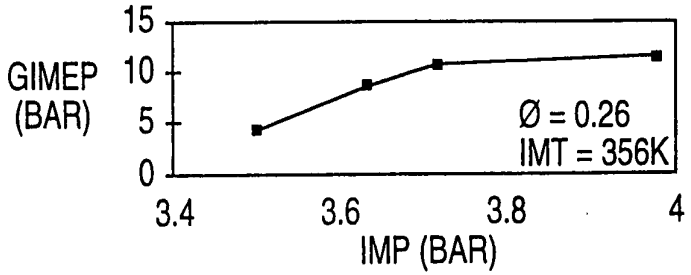


FIG. 31f

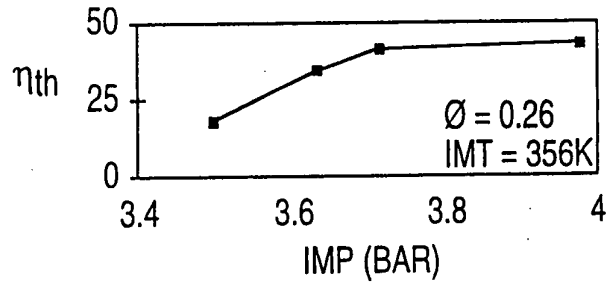


FIG. 31g

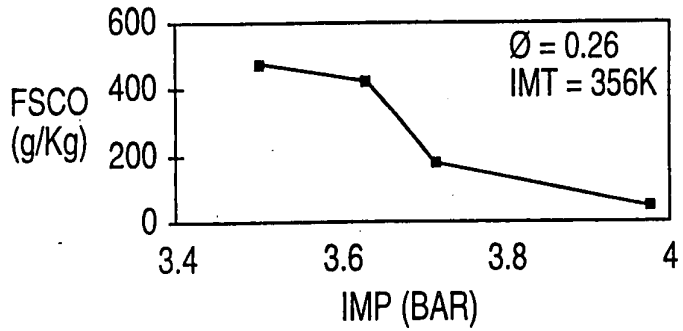


FIG. 31h

FIG. 31i

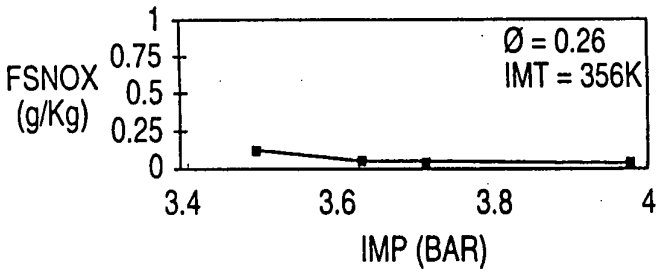


FIG. 31j

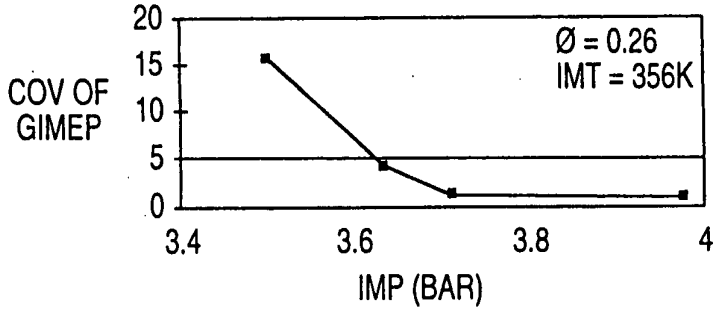


FIG. 31k

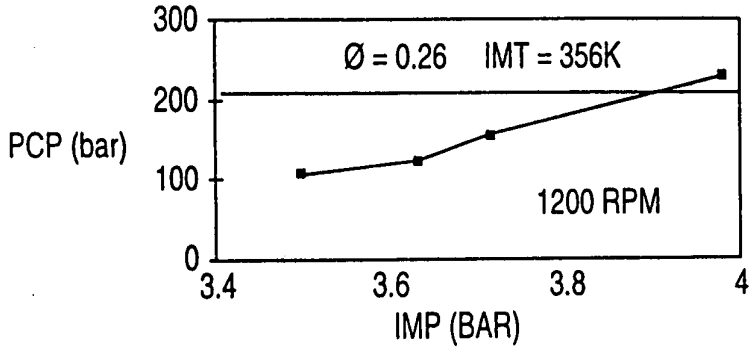


FIG. 31l

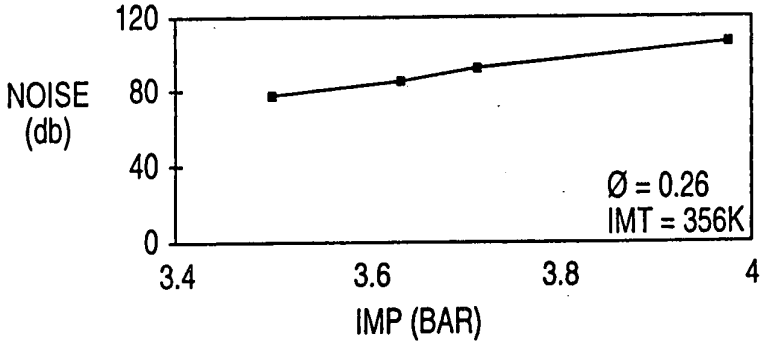


FIG. 31m

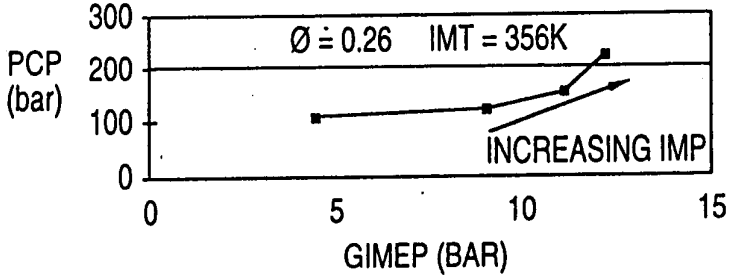


FIG. 32

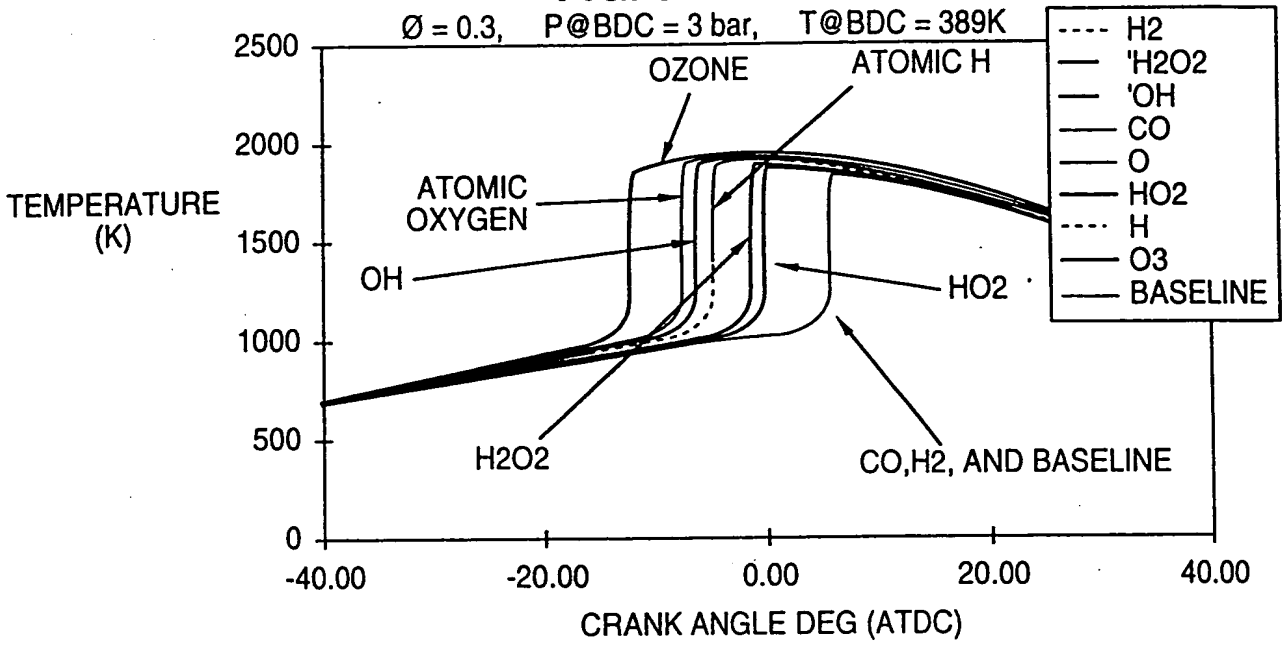

Ø = 0.3, P@BDC = 3 bar, T@BDC = 389K
TEMPERATURE (K)
2500
2000
1500
1000
500
0
OZONE
ATOMIC H
ATOMIC OXYGEN
OH
HO2
H2O2
CO,H2, AND BASELINE
H2
'H2O2
'OH
CO
O
HO2
H
O3
BASELINE
-40.00
-20.00
0.00
20.00
40.00
CRANK ANGLE DEG (ATDC)

FIG. 33

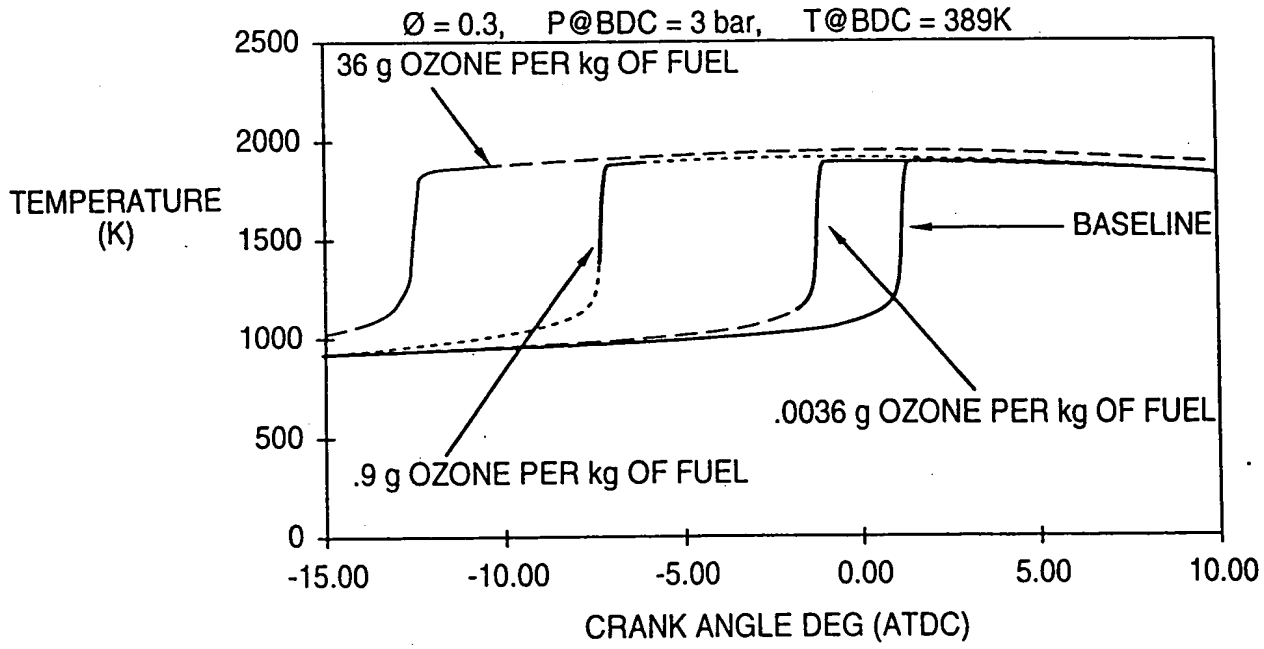

Ø = 0.3, P@BDC = 3 bar, T@BDC = 389K
TEMPERATURE (K)
2500
2000
1500
1000
500
0
36 g OZONE PER kg OF FUEL
BASELINE
.0036 g OZONE PER kg OF FUEL
.9 g OZONE PER kg OF FUEL
-15.00
-10.00
-5.00
0.00
5.00
10.00
CRANK ANGLE DEG (ATDC)

FIG. 34

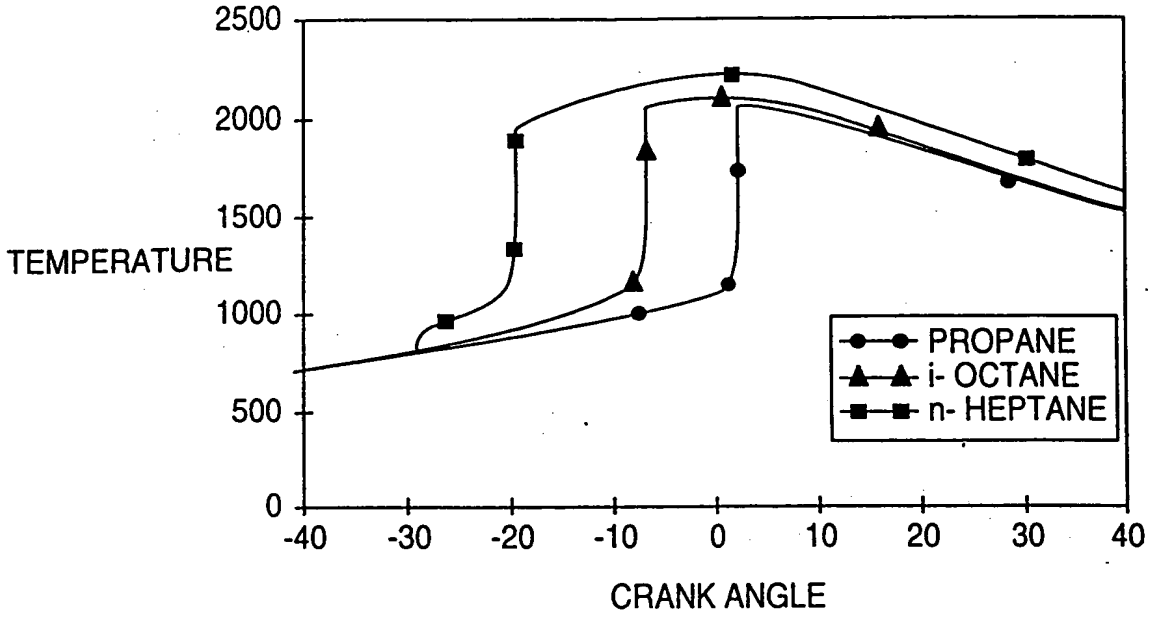


FIG. 35

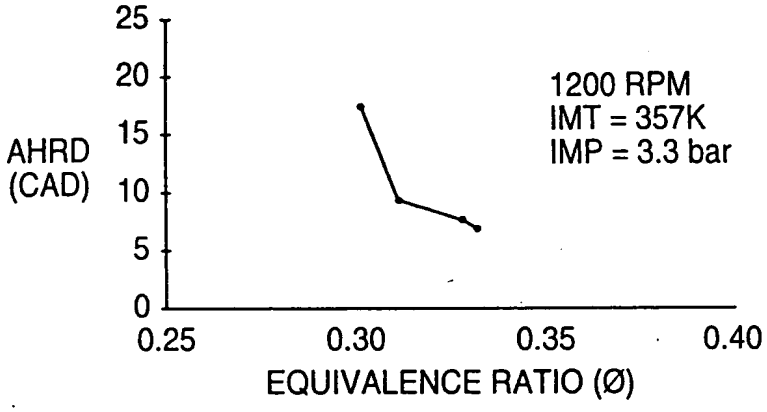


FIG. 36

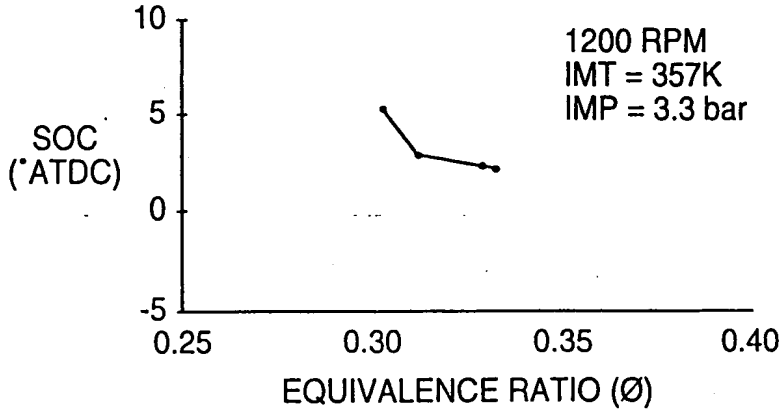


FIG. 37

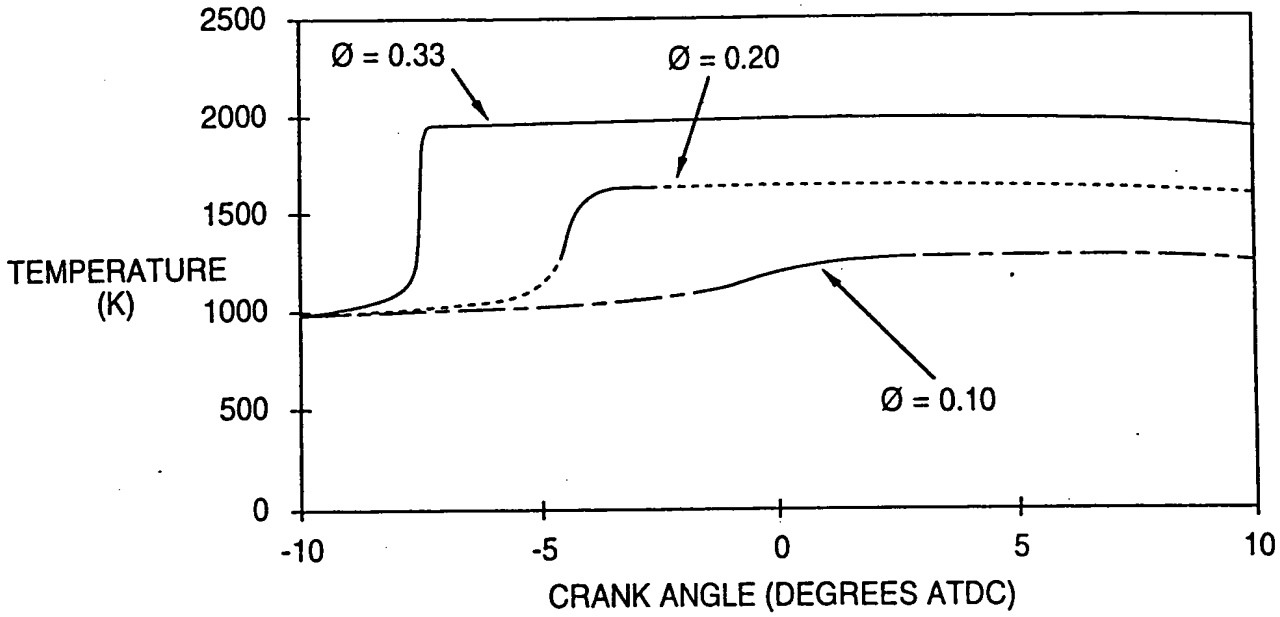

2500
2000
1500
1000
500
0
TEMPERATURE (K)
Ø = 0.33
Ø = 0.20
Ø = 0.10
-10
-5
0
5
10
CRANK ANGLE (DEGREES ATDC)

FIG. 38

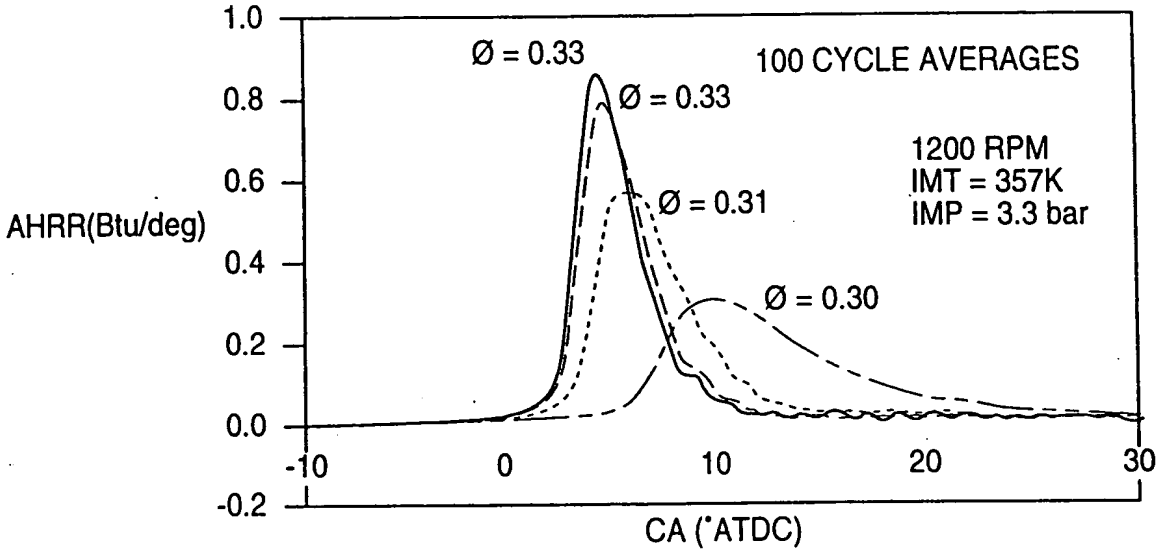

1.0
0.8
0.6
0.4
0.2
0.0
-0.2
AHRR(Btu/deg)
Ø = 0.33
100 CYCLE AVERAGES
Ø = 0.33
1200 RPM
IMT = 357K
IMP = 3.3 bar
Ø = 0.31
Ø = 0.30
-10
0
10
20
30
CA (°ATDC)

FIG. 39

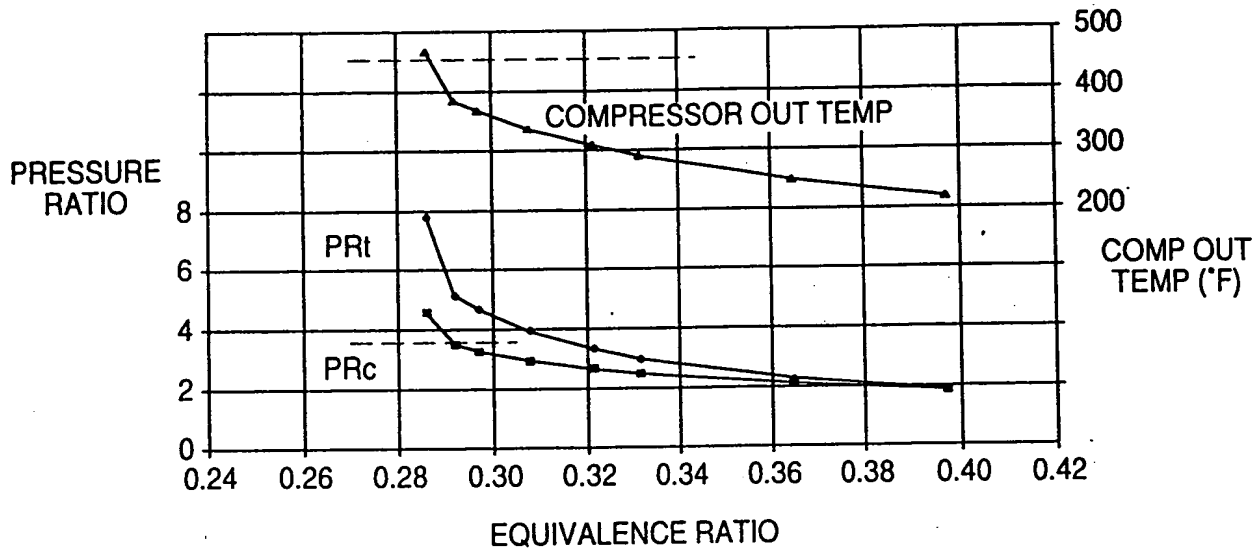

PRESSURE RATIO
8
6
4
2
0
PRt
PRc
COMPRESSOR OUT TEMP
500
400
300
200
COMP OUT TEMP (°F)
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
0.40
0.42
EQUIVALENCE RATIO

FIG. 40

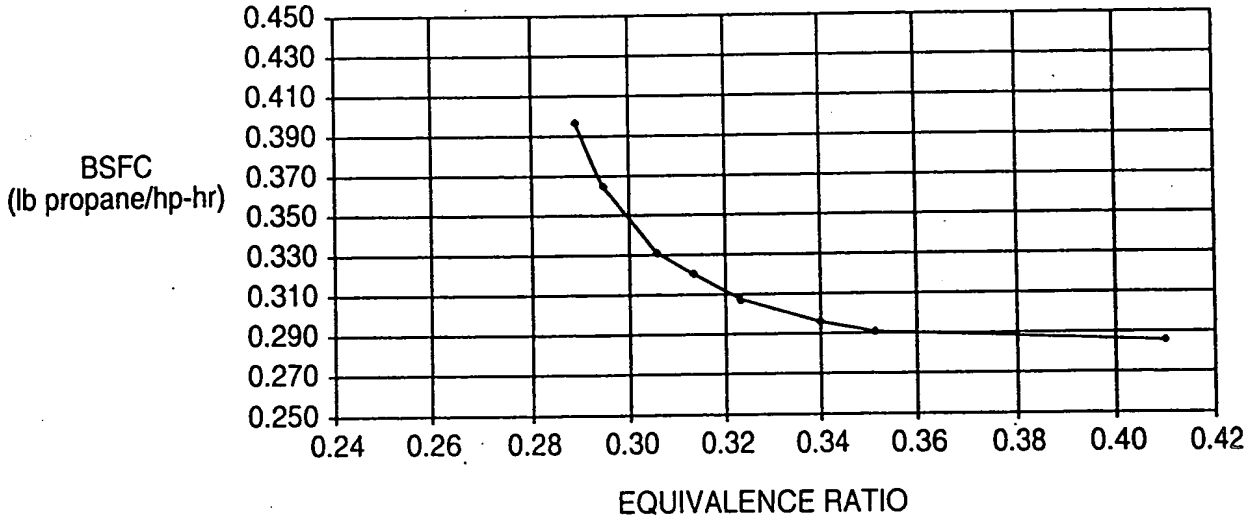

BSFC (lb propane/hp-hr)
0.450
0.430
0.410
0.390
0.370
0.350
0.330
0.310
0.290
0.270
0.250
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
0.40
0.42
EQUIVALENCE RATIO

FIG. 41

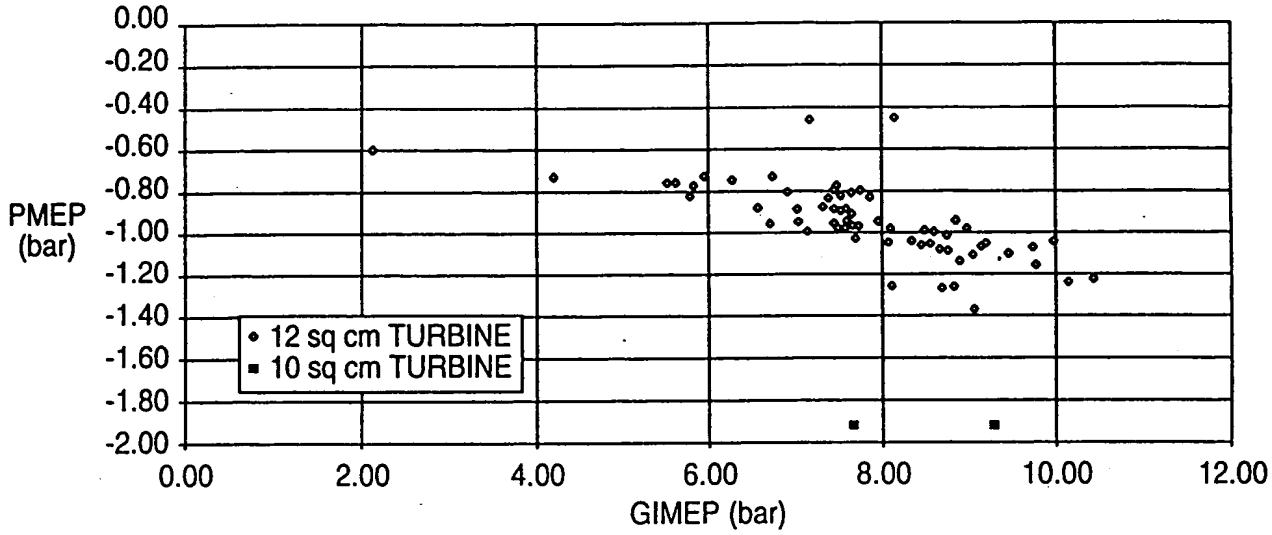

0.00
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
-1.80
-2.00
PMEP (bar)
12 sq cm TURBINE
10 sq cm TURBINE
0.00
2.00
4.00
6.00
8.00
10.00
12.00
GIMEP (bar)

FIG. 42

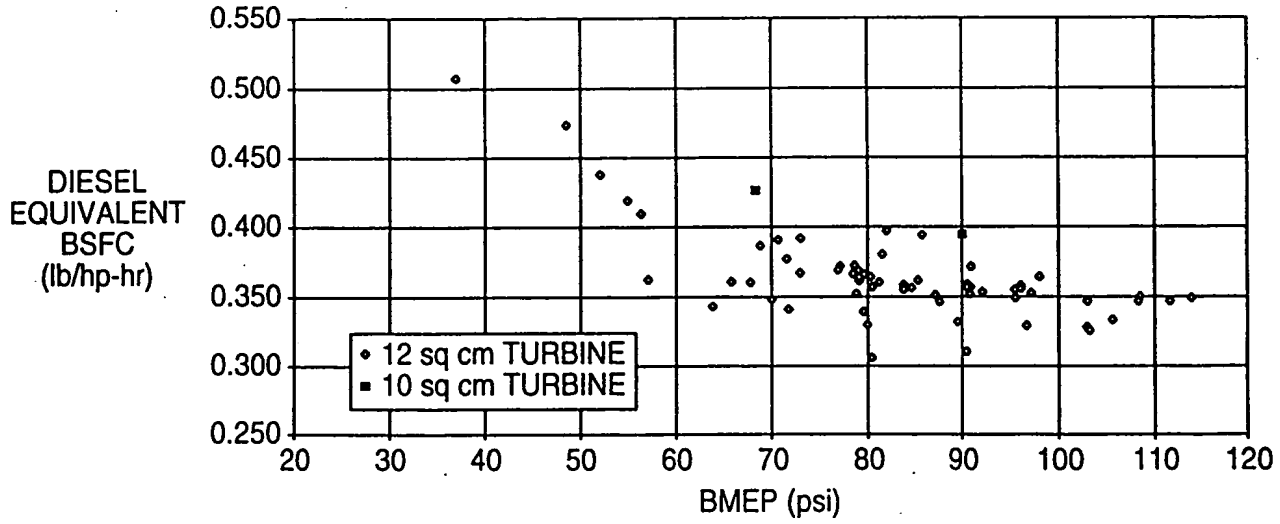

0.550
0.500
0.450
0.400
0.350
0.300
0.250
DIESEL EQUIVALENT BSFC (lb/hp-hr)
12 sq cm TURBINE
10 sq cm TURBINE
20
30
40
50
60
70
80
90
100
110
120
BMEP (psi)

FIG. 43

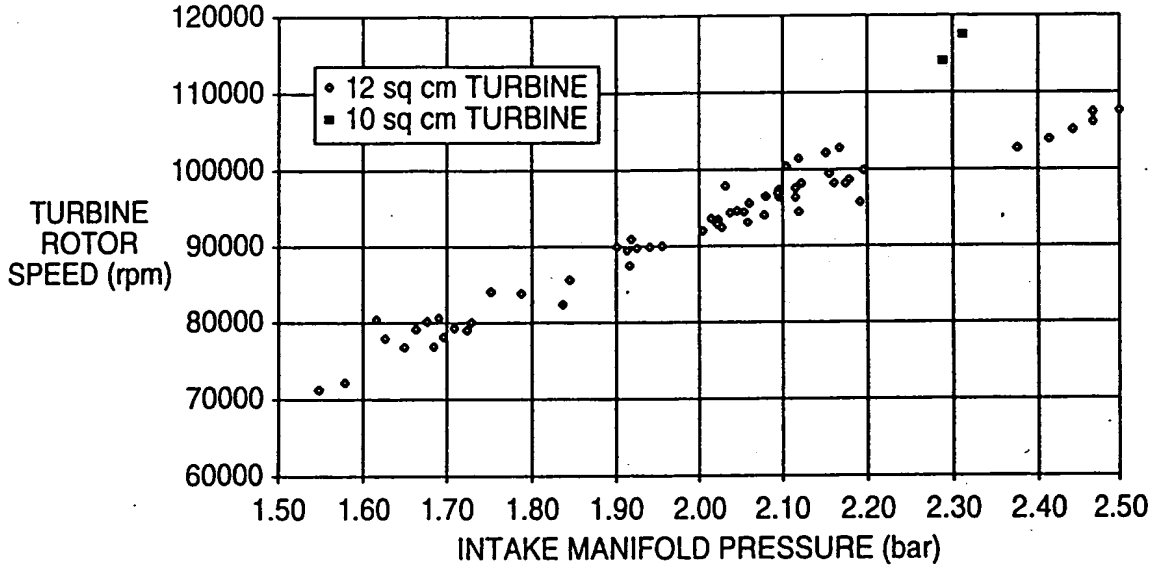

120000
110000
100000
90000
80000
70000
60000
TURBINE ROTOR SPEED (rpm)
12 sq cm TURBINE
10 sq cm TURBINE
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50
INTAKE MANIFOLD PRESSURE (bar)

FIG. 44

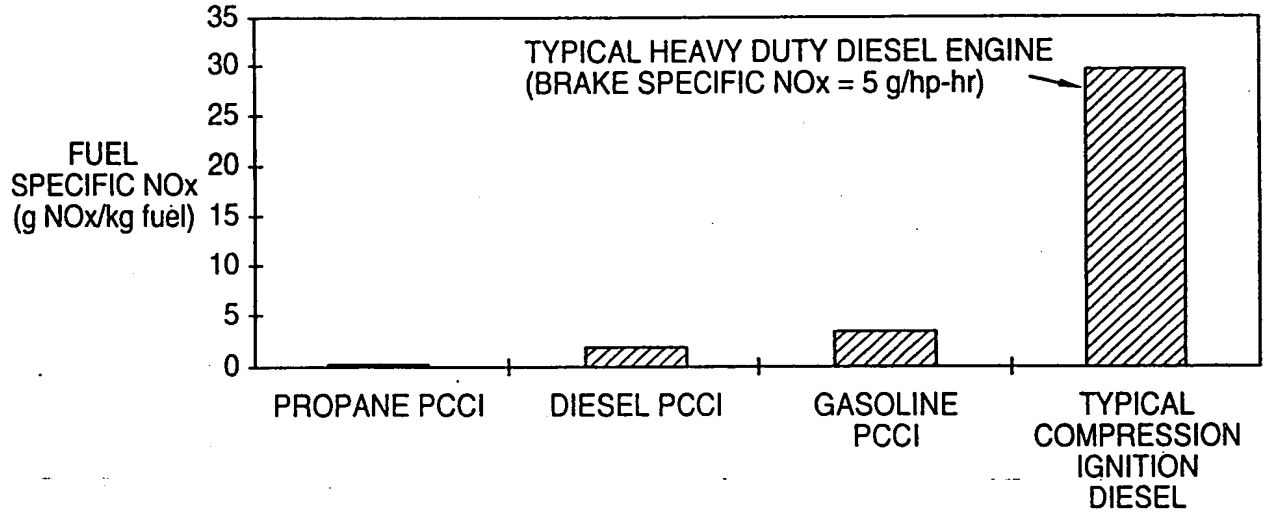

35
30
25
20
15
10
5
0
FUEL SPECIFIC NOx (g NOx/kg fuel)
TYPICAL HEAVY DUTY DIESEL ENGINE
(BRAKE SPECIFIC NOx = 5 g/hp-hr)
PROPANE PCCI
DIESEL PCCI
GASOLINE PCCI
TYPICAL COMPRESSION IGNITION DIESEL

FIG. 45

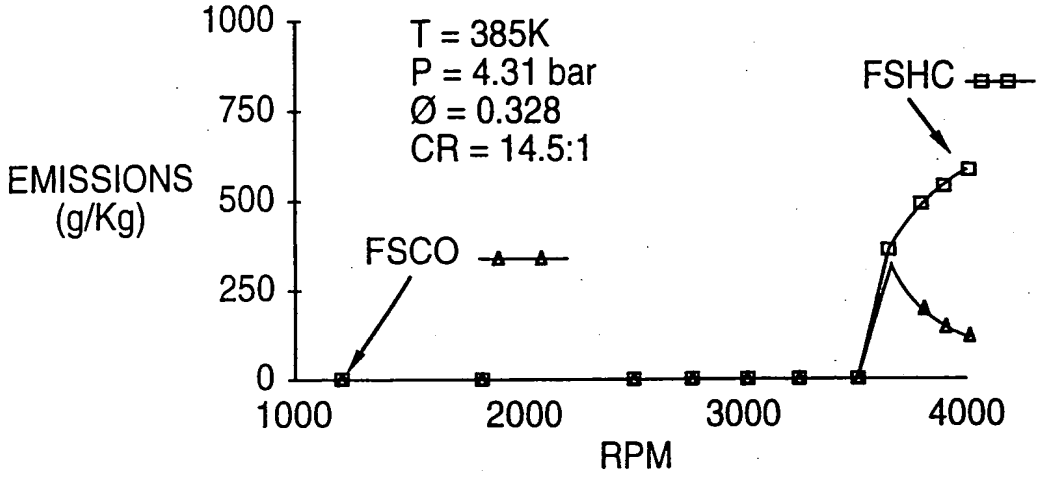


FIG. 46

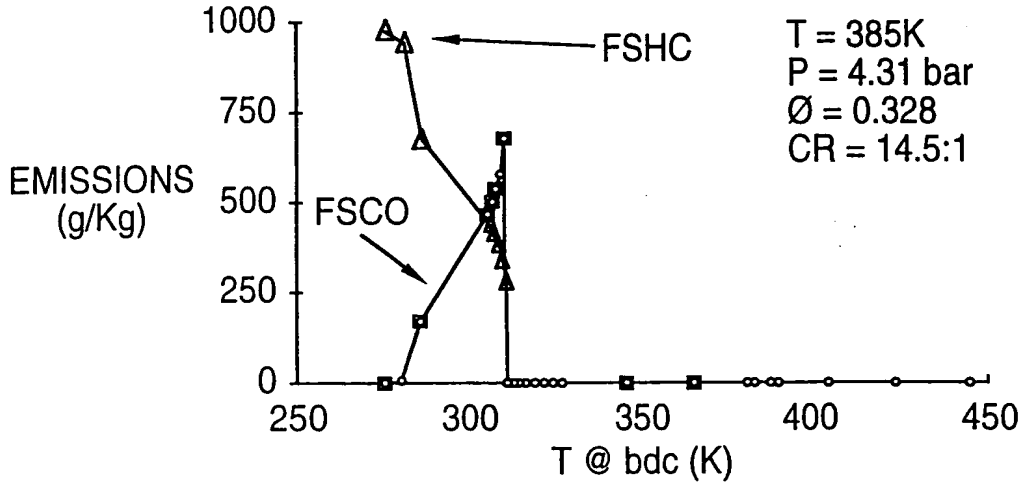


FIG. 47

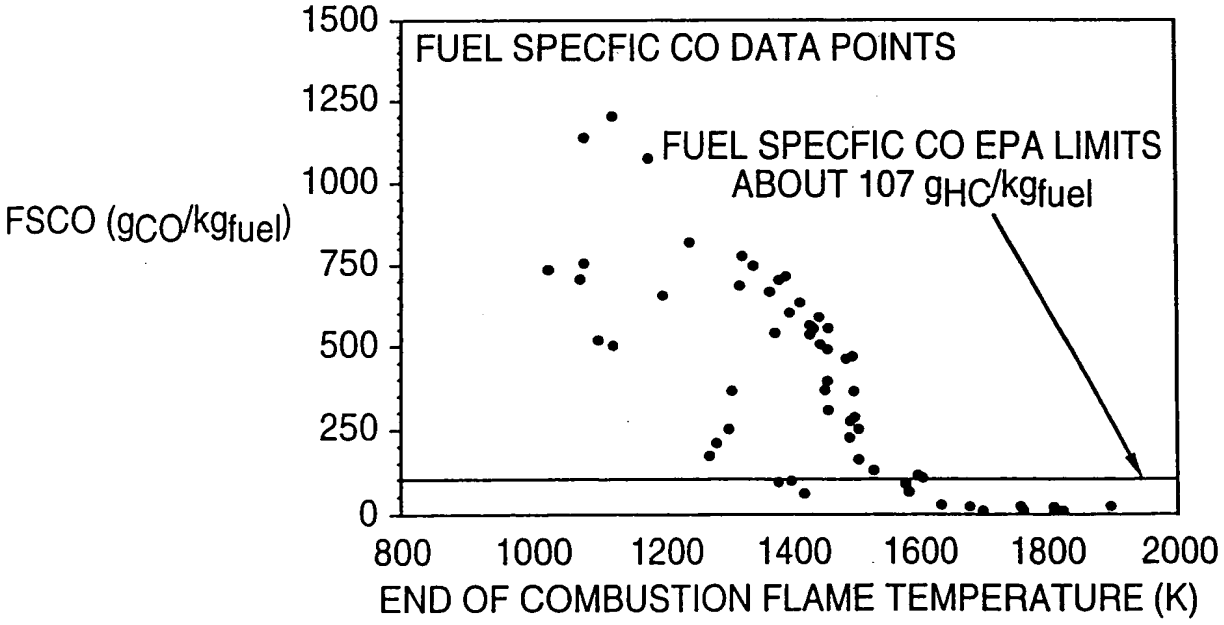


FIG. 48a

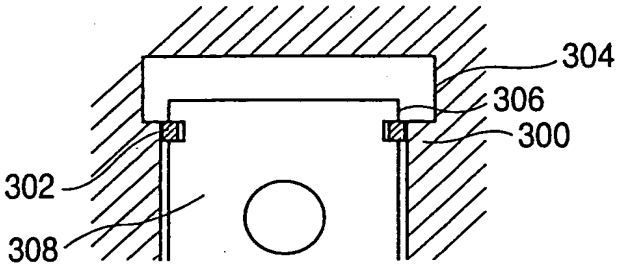


FIG. 48b

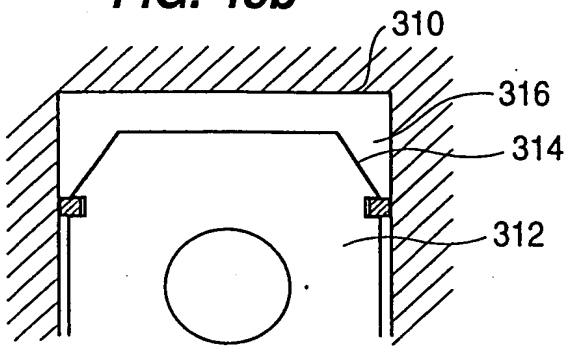


FIG. 49

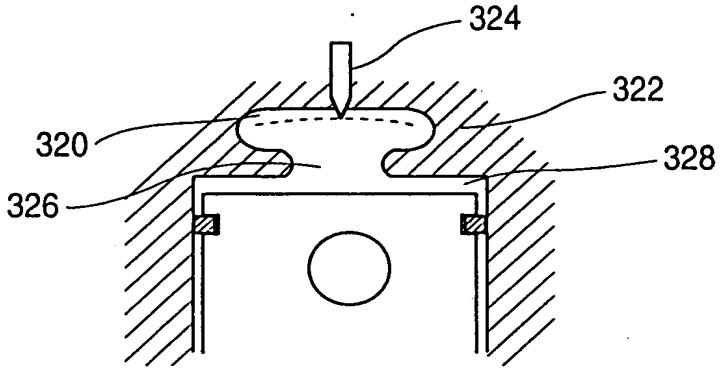


FIG. 50a

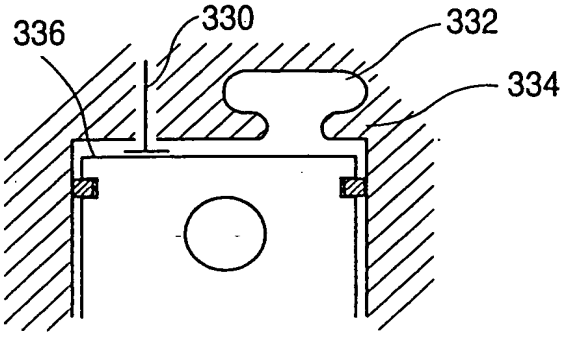


FIG. 50b

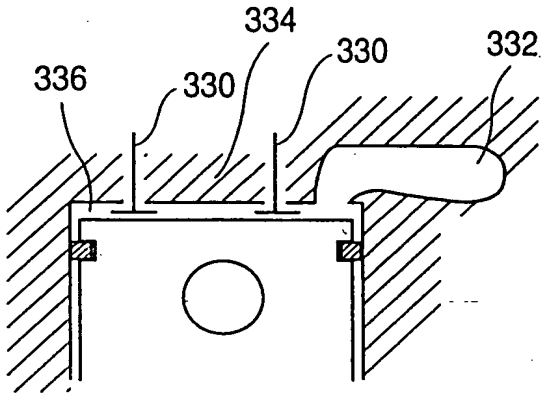
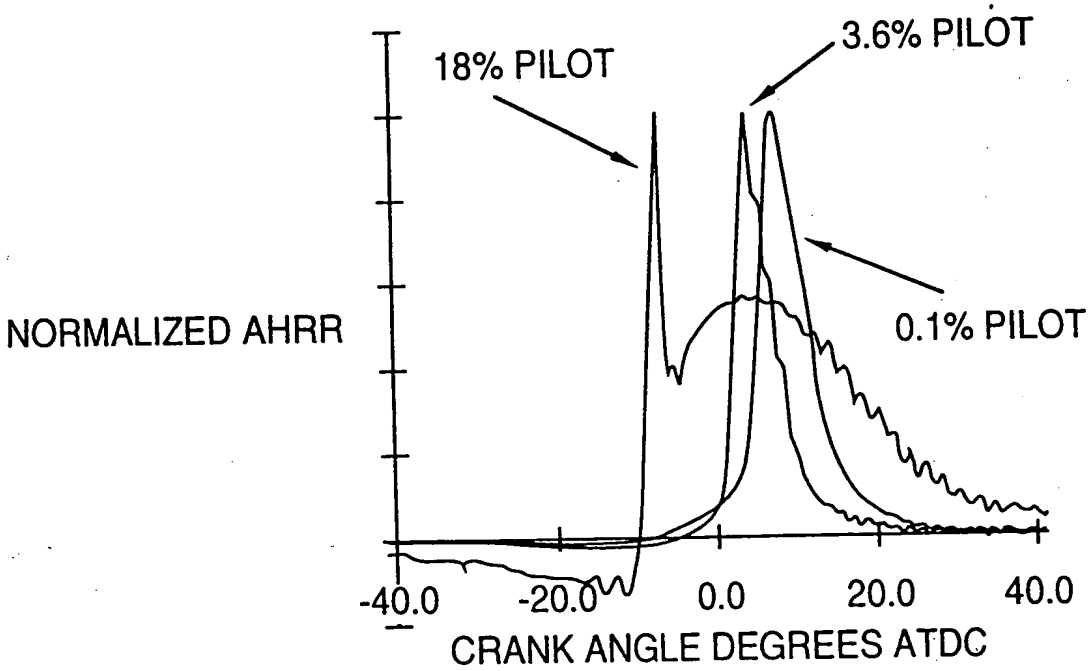


FIG. 51


18% PILOT
3.6% PILOT
0.1% PILOT
NORMALIZED AHRR
-40.0
-20.0
0.0
20.0
40.0
CRANK ANGLE DEGREES ATDC